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NEOGENE EVOLUTION OF THE CENTRAL TEXAS LANDSCAPE AND THE EDWARDS AQUIFERS AFTER BALCONES FAULTING

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ABSTRACT

The Edwards Plateau and the Balcones Fault Zone (BFZ) dominate the geology and physiography of Central Texas. The Edwards Plateau was formed during early Miocene time by uplift of the area west and north of the arcuate BFZ. The Albian Edwards Group was a continuous sheet of resistant shallow-shelf carbonate strata that covered all of Central Texas: the Edwards Plateau, BFZ, and subsurface of the Central Texas Platform. At the time of first Balcones faulting, the resistant Edwards Limestone was already widely exposed west and north of the BFZ. Regional headward erosion and dissolution following Balcones faulting progressively stripped away Edwards strata, leaving steep, ragged bluffs that delineated the boundaries of the Edwards Plateau. Just as geological maps outline the Edwards Plateau today, a reconstruction of past Edwards Limestone outcrop locations tracks the stages of westward and northern erosional retreat through Miocene, Pliocene, Pleistocene and Holocene times.

The sequential evolution of the Central Texas landscape is integrated with independent evidence from 6 related geological processes and events to generate a holistic account of Edwards Plateau and BFZ history since early Miocene time:

1. **Incised meanders of Edwards Plateau rivers and streams inboard and peripheral to the BFZ, which were probably inherited from early Paleocene settings, then greatly amplified by Balcones-related uplift.**
2. **The entire Edwards (BFZ) aquifer (recharge, artesian, and saline zones) has operated as an integrated geohydrologic system, evolving under the influence of (a) the location of the eroding outcrop of the Del Rio Clay (the artesian aquifer top-seal); and (b) mixing of phreatic and saline formation waters along the saline water interface, which promoted hypogenic porosity creation.**
3. **High porosity and permeability of Edwards strata in the central sector of the Edwards (BFZ) aquifer are related to (a) a longer period of increased stream gradients and stream piracy in that sector; (b) a wider BFZ with greatest vertical displacement and more faults and fractures; (c) major discharge points at Comal and San Marcos springs, the lowest elevations in the central sector of the trend; and (d) hypogenic processes creating karstic porosity along the artesian/saline water interface.**
4. **Between 14 and 10.5 Ma, the Colorado River formed its Great Bend, when it shifted its course about 35 mi north and east, after eroding through Cretaceous strata onto hard, northeast-dipping Paleozoic beds. This shift also generated the marked asymmetry of the Colorado drainage basin, with short tributaries on the east, and long straight tributaries on the west.**
5. **Multiple levels of horizontal cave development (youngest downward) in the western Edwards Plateau suggest that the thickness of the unconfined Edwards Plateau aquifer was greatest immediately following Balcones faulting, and declined afterward in stages as erosion reduced the area of surface recharge and increased the number of headwater springs.**
6. **The post-Balcones Medina Arch induced concave-upward stream profiles in streams originating around its apex: Pedernales, Blanco, Guadalupe, Medina, Frio, and East Nueces rivers.**

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INTRODUCTION

The Edwards Plateau is an immense tableland that dominates the geography of west-central Texas, covering more than 30,000 mi^2 (Fig. 1). Along its northern margin, the Plateau rises 100 to 300 ft above the adjacent rolling prairies; along its southern margin, it stands 500 to 1500 ft higher than the adjacent coastal plains of the Rio Grande Embayment. On the east, where the Plateau is dissected by east-flowing rivers, high-standing interfluvial divides rise 100 to 400 ft above valleys cut into older formations. Farther west, thin (<30 ft) erosional remnants of

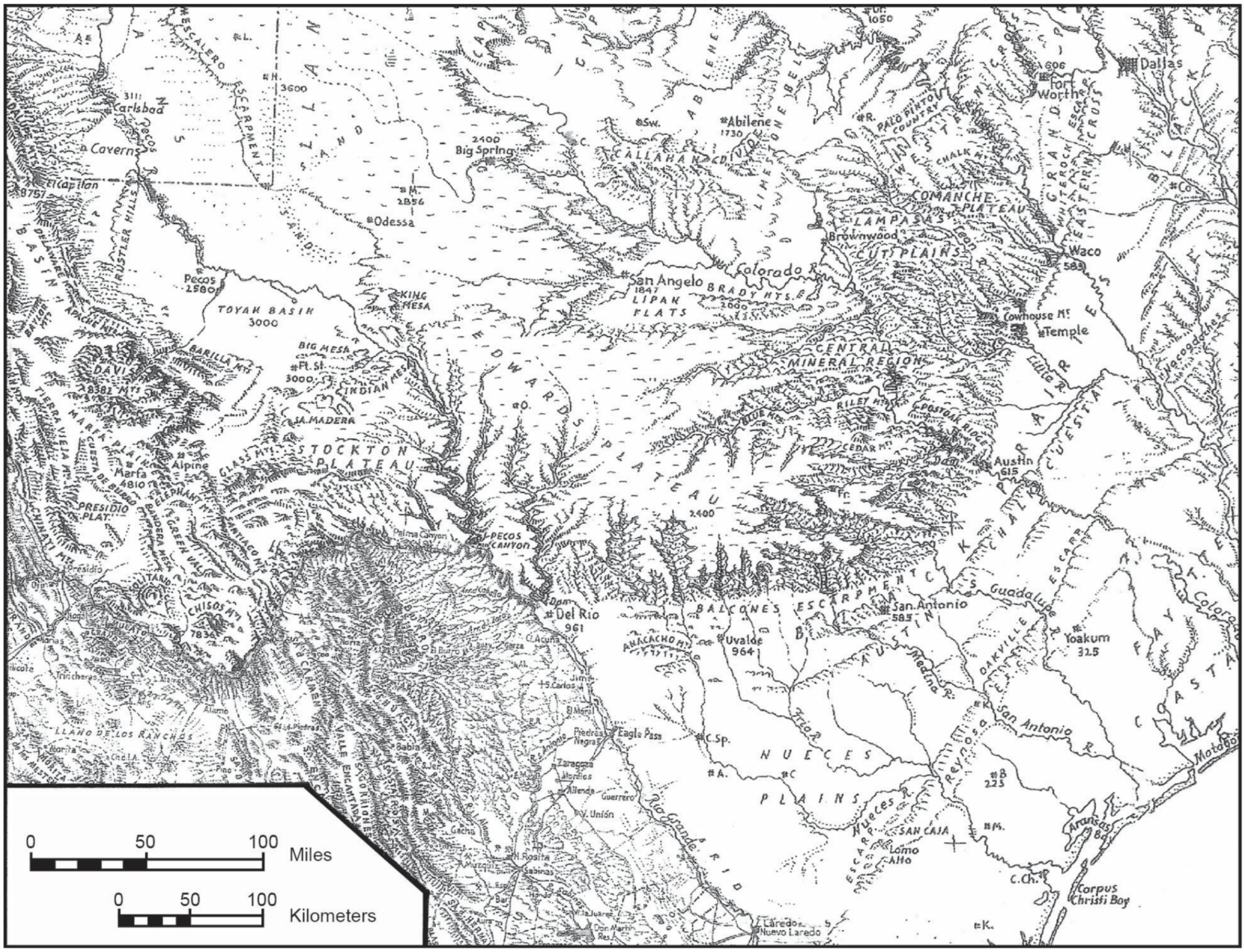

Figure 1. Physiography of Central Texas (modified after Rose, 2012, after Erwin J. Raisz, 1957, 1964, landform maps with permission).

deeply weathered Buda Limestone overlie the Edwards Group on flat, high divides in the heart of the Plateau. The Edwards Plateau extends westward across the Pecos River, where it is sometimes called the Stockton Plateau. To the northwest, from around Odessa to Sweetwater, the upper surface of the Edwards Plateau merges almost imperceptibly with the younger high plains (or Llano Estacado) of West Texas and the Texas Panhandle (Rose, 2012).

The Plateau is the topographic and geomorphic expression of a thick, widespread, flat-lying sequence of Lower Cretaceous (mostly middle and upper Albian) limestones and dolostones assigned to the Edwards Group, which thickens southwestward, from about 350 ft on the north to more than 800 ft along the southern edge of the Plateau (Rose, 1972, 2017). Edwards carbonate strata are generally harder and more resistant to weathering and erosion than the underlying softer, Trinity sandstones and marls, which is why the Edwards Plateau is a high-standing topographic feature, dissected and rough-edged around its margins (Rose, 2004).

The eastern and southern margins of the Edwards Plateau are a continuous fault-line scarp adjoining the Gulf Coastal Plain, formed when early Miocene normal faulting elevated the area west and north of the BFZ, and subsequent subaerial erosion and dissolution dissected the eastern margins of the Plateau into a serrate, digitate landscape known as the Texas Hill Country.

The Edwards Plateau and the Balcones Fault Zone

The regional geologic map of Central Texas (Fig. 2) is dominated by two geologic features: (a) the arcuate BFZ, marking the suture along which the Edwards Plateau was uplifted above the adjacent Gulf Coastal Plain; and (b) the Plateau itself, whose dissected interfluvial divides reach eastward from its elevated western mass like bony fingers. Close examination of this map of Central Texas prompts the realization that the outcropping base of the Edwards Limestone represents only the present stage in the inexorable retreat, by headward erosion, of the base of the dissected margins of the Edwards Plateau, westward and northward from the BFZ. This retreat began about 20 Myr ago, when the Edwards Plateau was uplifted with Balcones faulting, and it will continue until the high-standing Plateau is entirely consumed by headward erosion, or represented only by isolated remnants of Edwards Limestone, perhaps 20–30 Myr from now. Such remnants exist today, e.g., the Callahan Divide on the northern margins of the Edwards Plateau. The Lampasas Cut Plain, west of Belton and Waco, represents a less-elevated part of

Figure 2. Geologic/geomorphic provinces, Central Texas (modified after Rose, 2016).

the Edwards Plateau in which the resistant Edwards Limestone grades laterally northward and eastward into softer strata of the East Texas Basin.

The Edwards Aquifers

There are two Edwards aquifers:

(1) The Edwards Plateau aquifer is a widespread unconfined aquifer in the lower part of the Edwards Group throughout the Edwards Plateau region. Although this aquifer is more formally known as the Edwards-Trinity (Plateau) aquifer (George et al., 2011), it will be referred to herein simply as the Plateau aquifer.

(2) The Edwards (BFZ) aquifer consists of an updip unconfined recharge zone, and a downdip artesian zone where it is overlain by the impervious Del Rio Clay. The Barton Springs (Edwards) aquifer is a small northern segment of the Edwards (BFZ) aquifer, separated from its larger southern counterpart by a transient groundwater divide in eastern Hays County, midway between San Marcos and Austin.

Purpose and Organization

The landscape of the Texas Hill Country and Edwards Plateau has evolved since the onset of Balcones faulting, early in the Miocene Epoch. The present-day drainage system, containing relict features such as incised meanders, evidence of the northeasterly migration of the Colorado River, and continued retreat by headward erosion of the margins of the Edwards Plateau, are all part of that evolution. The Edwards Plateau aquifer and Edwards (BFZ) aquifer, as well as regional karst development, also evolved as a direct result of Balcones faulting and associated regional uplift of the Plateau. The fundamental aim of this report is to integrate all such observed phenomena into a holistic geologic, geomorphic, hydrologic *historical* account.

After reviewing foundational background material on regional geology and Edwards Group stratigraphy, the report presents salient facts (including new maps and other data), interpretations, discussions, and conclusions in four sections: (1) stream drainage patterns; (2) stream profiles of area rivers; (3) Edwards Plateau slope-retreat following first Balcones faulting; and (4) Evolution of both Edwards aquifers (which is largely

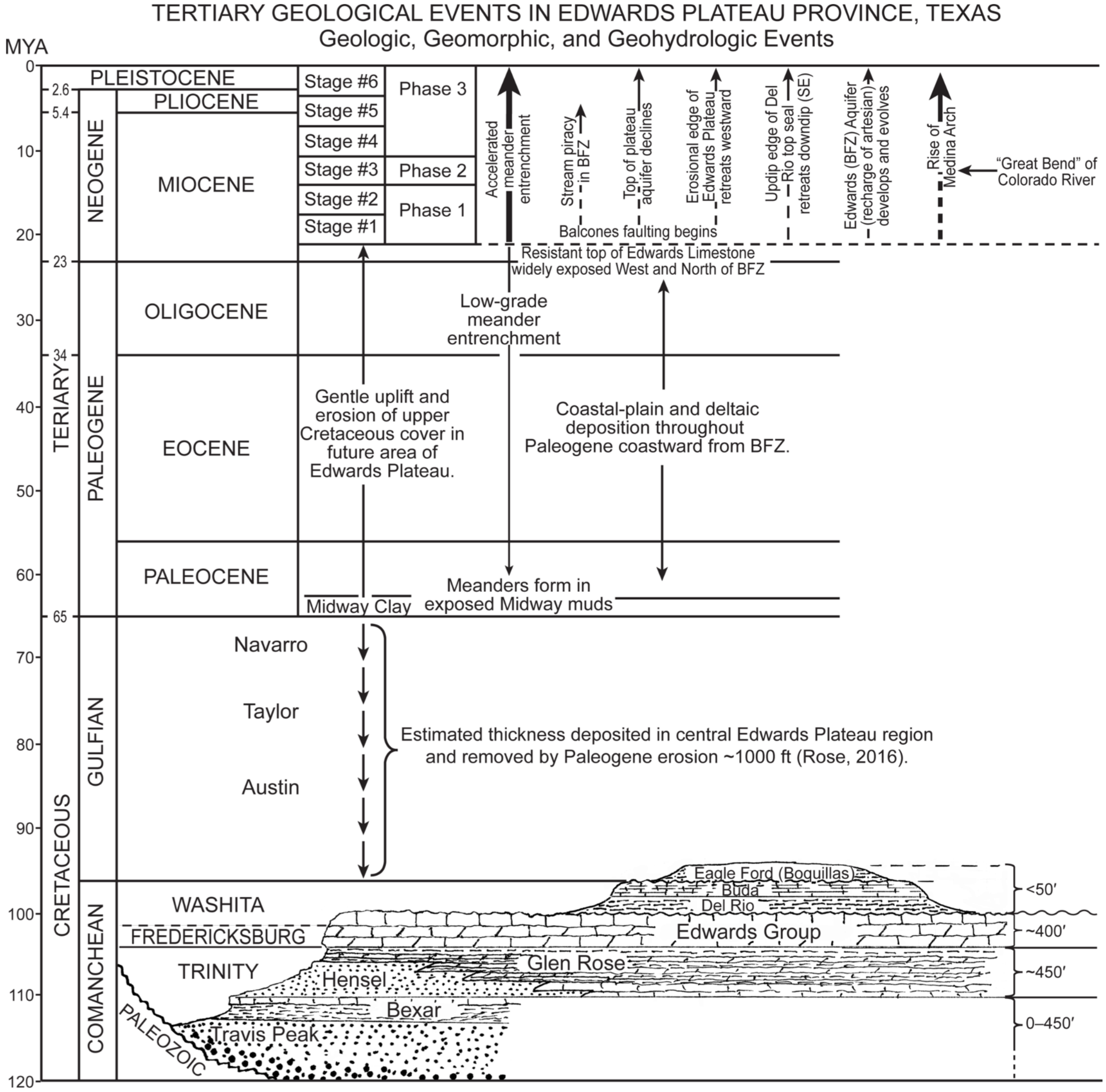

Figure 3. Tertiary geological events in the Edwards Plateau province, Texas.

based on published work of others). The concluding section of the report combines essential interpretations and conclusions into an integrated historical account, told in three successive geologic phases. This account is summarized graphically by Figure 3, which may be a useful as reference while reading the report.

REGIONAL GEOLOGIC ELEMENTS

The structural-geologic history of Central Texas is long and complex. Figure 4 shows structural features that are important to the geologic history of Central Texas in general, and Neogene landscape evolution in the area west and north of the BFZ, in particular. Figure 5 is a regional structure map on top of the Edwards Group and equivalent formations. Pertinent geologic features are reviewed here in chronological order.

Llano Uplift

The Llano Uplift is a geologically ancient domal feature located mostly in Llano, Mason, San Saba, Gillespie, and Blanco counties. Surrounding its Precambrian metamorphic and igneous core is a thick sequence of faulted lower Paleozoic sedimentary formations, which is succeeded on its northern margin by a thick Permo-Carboniferous succession of terrigenous, carbonate, and evaporitic strata.

The Llano Uplift seems to have served as a long-time structural buttress for younger geological trends. The outline of the Llano Dome (Ewing, 2005), is shown on maps of this report where pertinent. Domal structural contours on top Edwards (Fig. 5) indicate that the Llano Uplift continued to act as a structurally positive feature after Edwards deposition. It is also generally accepted that the present gentle, uniform northwestward rise of the Plateau westward from the Llano Uplift is post-Miocene, related to the regional uplift of the Colorado Plateau to the northwest (Galloway et al., 2011).

Ouachita Structural Belt

In North and Central Texas, the Ouachita Structural Belt, described by Flawn et al. (1961), lies entirely in the subsurface. It passes from near Dallas southwesterly to the Austin area, then begins its westward swing under San Antonio and Uvalde. It is interrupted by the late Paleozoic Devils River Uplift near Del Rio, then bears northwesterly and finally westerly into the area of the Marathon Uplift, West Texas, where it comes to the surface. The Ouachita Structural Belt is thought to be the result of a late Paleozoic continental collision from the south. It consists of a

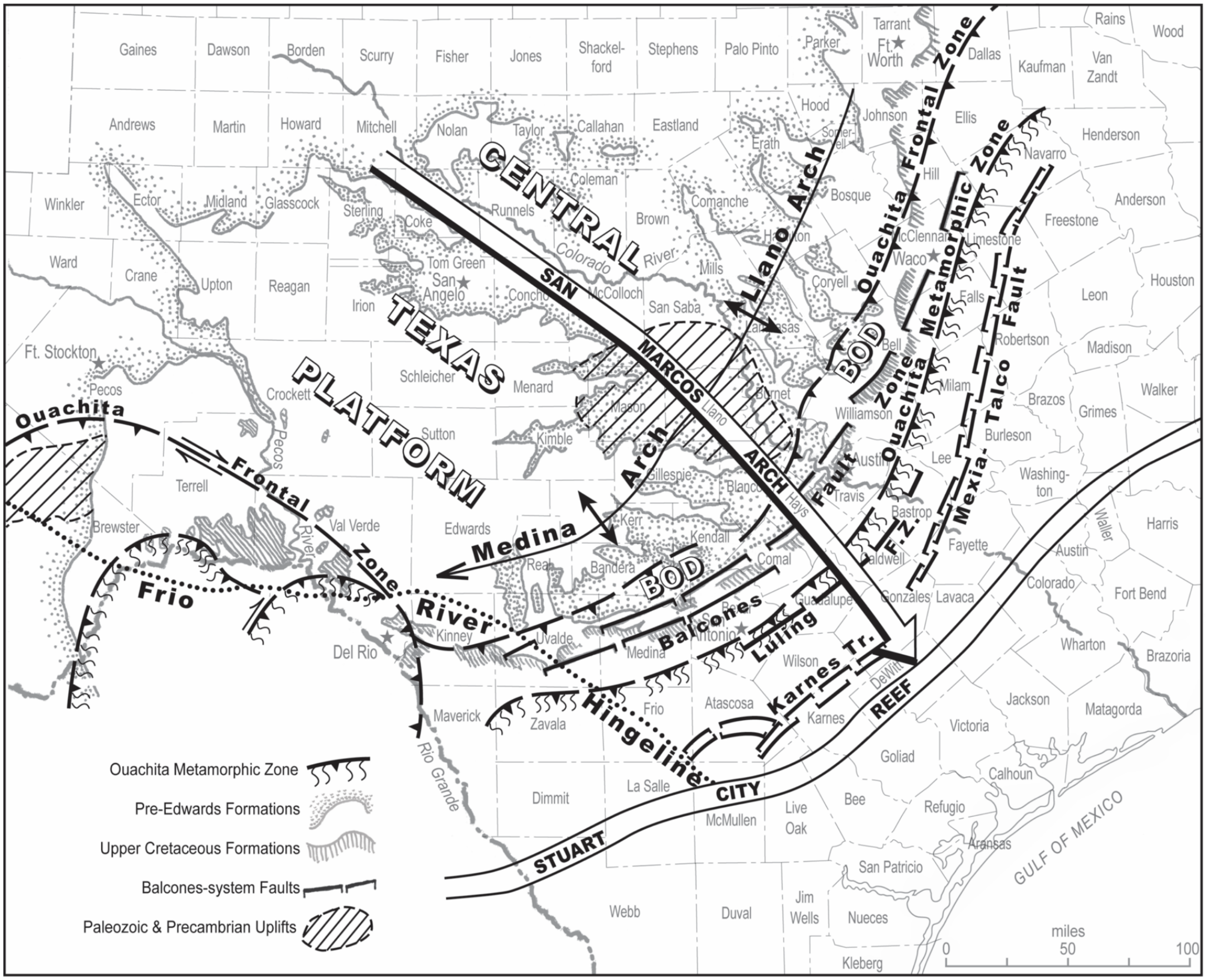

Figure 4. Regional structural elements, Central Texas (BOD = Balcones-Ouachita Downwarp) (from Rose, 2016).

western/northern frontal zone of Appalachian-style folds and thrust faults involving Paleozoic rocks through middle Pennsylvanian, and an eastern/southern metamorphic zone, of uncertain age and origin. In the subsurface, the Ouachita structural belt lies buried beneath Upper Jurassic and Lower Cretaceous strata and appears to wrap around the Llano Uplift. Its importance to this report is that the Neogene BFZ hews faithfully to the medial sector of the subsurface Ouachita Structural Belt, between the frontal thrusted zone and the metamorphic belt.

Balcones/Ouachita Downwarp (BOD)

The regional downwarp along the eastern, southeastern and southern margins of the Llano Uplift (Fig. 4), which appears on top Ordovician (Ellenburger Group) and base Cretaceous structure maps (Rose, 2016), is still present at top Edwards (Fig 5), where it lies inboard from the subsurface Ouachita structural belt. Dip rates eastward and southward from the Llano Uplift are consistently steeper on the deeper (older) mapping surfaces than on the shallow Edwards mapping datum. This persistent regional flexure represents the northern margin of the Gulf of Mexico basin. It will henceforth be referred to as the Balcones/Ouachita Downwarp (BOD), following Ewing (1991, 2005). It is important because it represents the most likely zone where Upper Cretaceous, Paleocene, and lower Eocene formations thinned or pinched out around the northern (cratonic) margin of the Gulf of Mexico.

Stuart City Reef

Fronting the gulfward edge of the Aptian-Albian Comanche Shelf was a narrow continuous belt of bioclastic carbonate sediments, the Stuart City Reef (Winter, 1961), which can be traced in the subsurface from northern Mexico across the Gulf coastal plain, past the shoreline of eastern Louisiana, continuing southeastward beneath the eastern Gulf of Mexico to the southern Florida Peninsula. The Stuart City Reef marked the northern margins of the Aptian and Albian Gulf of Mexico (Van Siclen, 1958; Winter, 1961; Rose, 1972). Seaward from the Stuart City Reef, Aptian/Albian water depths increased abruptly and consistently.

Central Texas Platform

The broad, structurally positive cratonic area comprising the area of the Texas Hill Country, Llano Uplift, Edwards

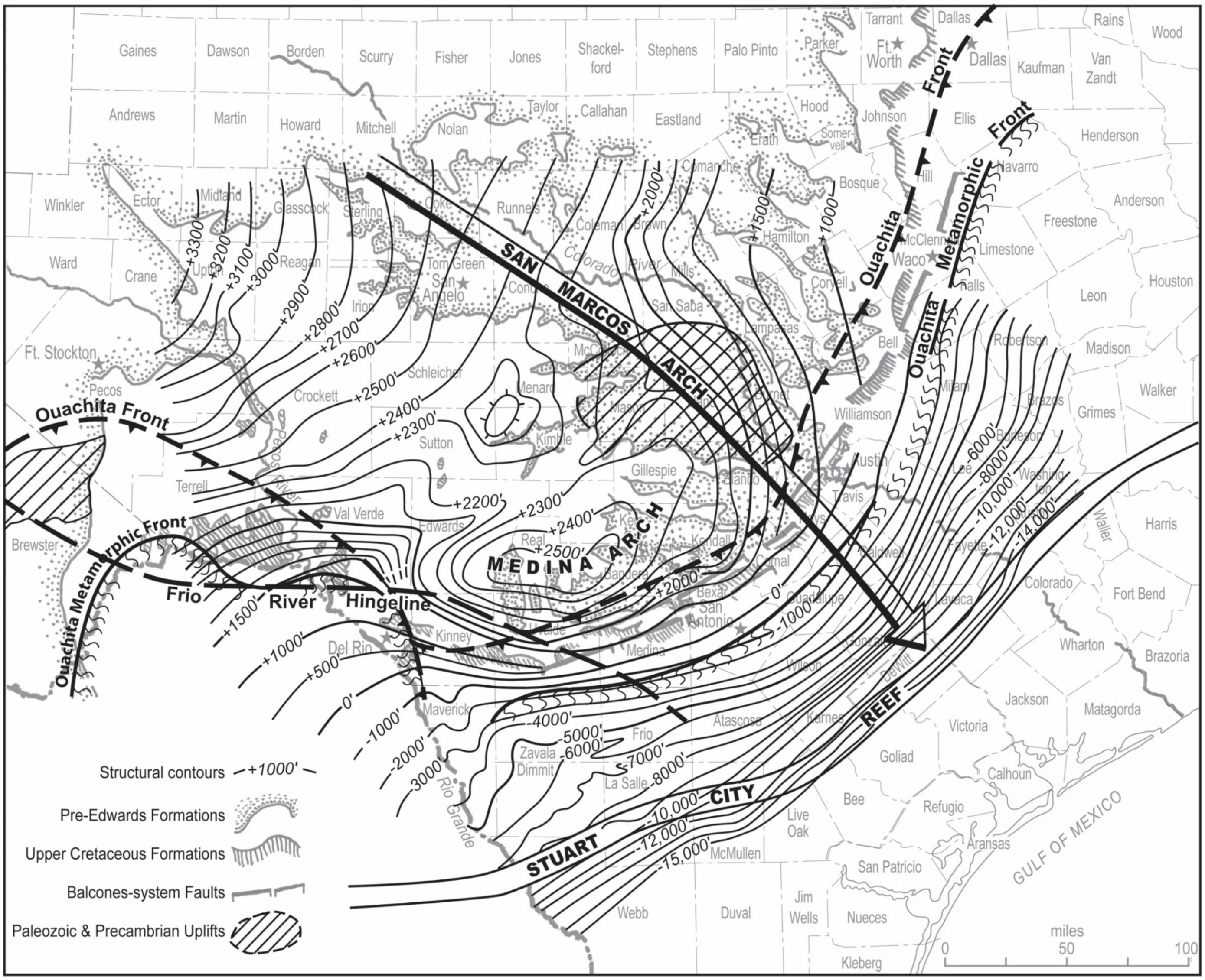

Figure 5. Regional structure on top Edwards Group and equivalents (Lower Cretaceous), Central Texas (from Rose, 2016).

Plateau, and subsurface beneath the Gulf Coastal Plain (Fig. 4), is known as the Central Texas Platform (Rose, 1972). This regional structural/depositional feature also has a strong paleogeographic component: it coincides with the presence of mostly clay-free Albian carbonate lithofacies that are characteristic of shallow-marine to restricted shelf-interior depositional environments, thus it serves as the genetic outline of the vast offshore carbonate bank—an immense sediment trap—that existed on the Comanche Shelf, protected by the Stuart City Reef and the San Marcos Arch.

San Marcos Arch

The structural axis of the Central Texas Platform is the San Marcos Arch, which extends southeastward from near Big Spring across the Llano Uplift, through San Marcos and Cuero, Texas (Fig. 5). In the subsurface, structural and stratigraphic evidence of this axis does not seem to extend coastward beyond the vicinity of Victoria. The San Marcos Arch is a gentle, asymmetric, persistent, positive structural axis affecting lithofacies and thickness patterns of the Edwards and associated formations, as well as Upper Cretaceous and Cenozoic formations. The Llano Uplift served as its structural apex (Rose, 2016).

Balcones Fault Zone (BFZ)

The BFZ involves Mesozoic formations as well as the underlying Ouachita facies. It consistently overlies the Ouachita structural belt, midway between the leading overthrusted and folded zone and the trailing metamorphic thrust front. It also lies consistently along the medial trend of the BOD (Figs. 4 and 5). Faulting is en echelon and extensional, mostly down to the southeast. The BFZ reaches maximum vertical displacement around San Antonio, approaching 2000 ft, and extends northward through Austin and Waco, finally dying out around Hillsboro, a distance of about 200 mi. Southwest from San Antonio, the BFZ reaches about 150 mi, across Medina County, north of Uvalde, dying out near Brackettville. It is consistently about 25 mi wide in the middle sector, narrowing toward each end as displacement diminishes. Ewing (2005, 2016) points out that, from San Antonio westward the major faults step to the right, whereas from San Marcos northward they step left. This generates a map pattern showing a southeast protrusion of the Edwards outcrop in the New Braunfels–San Marcos area, along the axis of the San Marcos Arch.

Collins and Woodruff (2001) showed (Fig. 6) that the BFZ at Austin consists of a major down-to-the-coast normal fault (the

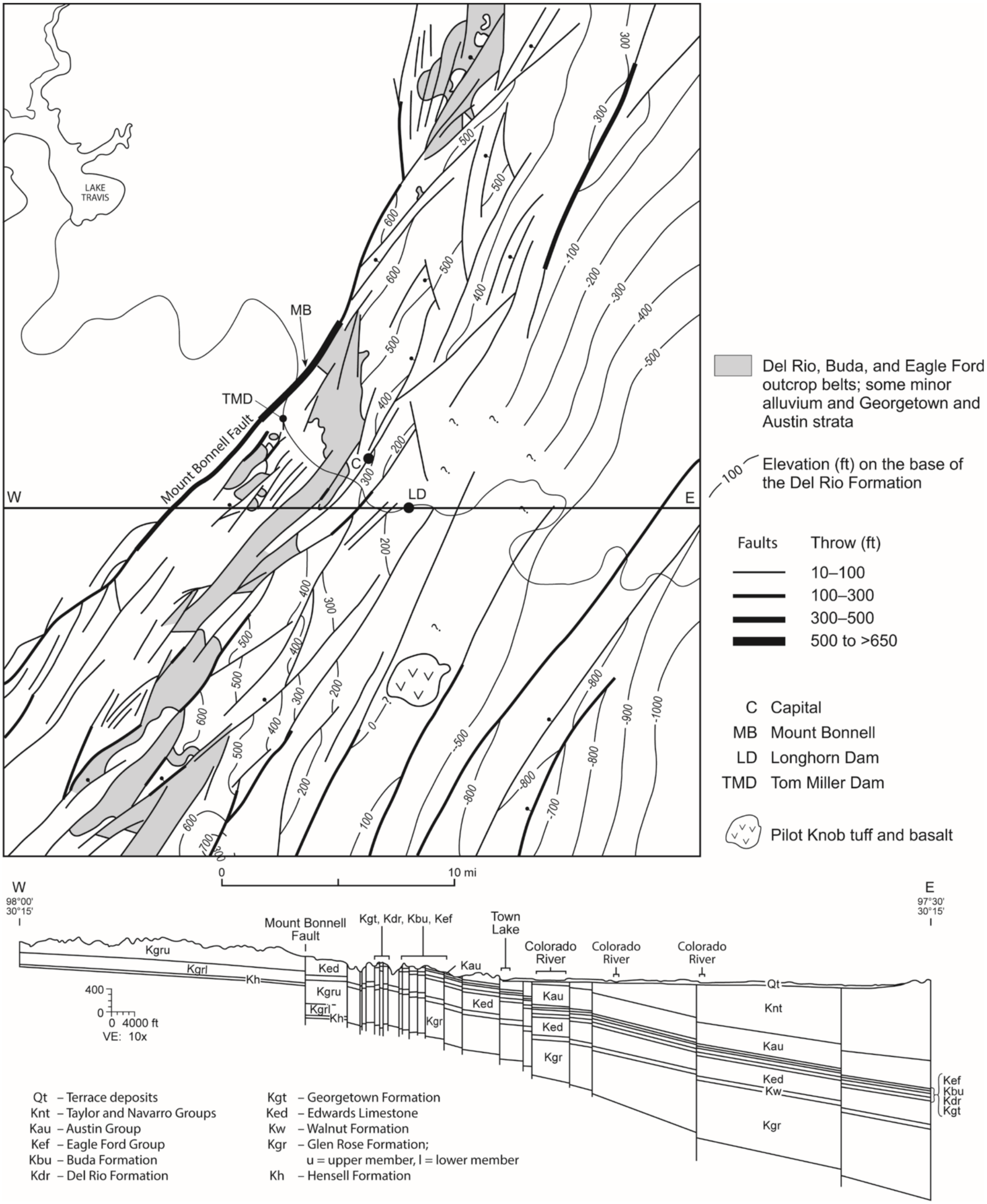

Figure 6. Map of BFZ in Austin area and geologic cross-section across map area (modified after Collins and Woodruff, 2001).

Mount Bonnell Fault) on the northwest, with a zone of both antithetic and synthetic faults about 20 mi wide—an apparent zone of structural adjustment to the master fault—adjoining on the southeast. Faults in the adjustment zone are more closely spaced in the 10 mi wide belt adjacent to the master fault than farther southeast. This would seem to imply that the first Balcones faulting at Austin involved the major downthrown master fault, with the adjacent zone of faults serving as subsequent adjustment faults. However, Collins and Hovorka's (1997) structure map and Collins' (2000) structural cross-section through New Braunfels shows more than a dozen synthetic faults in the 20 mi wide belt west of the downthrown master fault. There are only two antithetic faults along this entire cross-section, indicating almost all of the later structural accommodation was expressed as synthetic faulting.

The relationship between the BFZ and the underlying Ouachita structural belt remains obscure; most authors (e.g. King, 1961; Murray, 1961) have simply described the Ouachita trend as a zone of weakness in the upper crust, thus a more likely site for later faulting. Ewing (2005) identifies three possible origins: (1) reactivation of Ouachita thrusts and guide planes; (2) deeper Llano-style normal faults; or (3) keystone faults due to bending that dies out with depth. Hayman (2009) offers two alternate hypotheses: (1) uplift induced by sediment loading; and (2) thermal subsidence models.

Balcones faulting (and concurrent uplift of the eastern Edwards Plateau area) is widely accepted to have occurred in late Oligocene and early Miocene. In this report, it is taken to be 21 Ma (early Miocene, consistent with (Berggren et al., 1995a, 1995b), and for purposes of mapping 6 3.5 Myr stages of erosional removal. The eastern and southern margins of the Edwards Plateau were elevated above the Gulf Coastal Plain beginning about 20 Ma, during early Miocene (Weeks, 1945a, 1945b; Ely, 1957; Ragsdale, 1960; Galloway et al., 1982, 2000, 2011). This event left unmistakable sedimentary evidence, i.e., the common presence of sedimentary particles derived from Upper Cretaceous formations in the upper part of the Catahoula Formation (Oligocene) (Galloway, 1977), succeeded by an elongate carbonate and chert gravel-and-sand outwash plain in the Miocene Oakville Formation, whose outcrop belt lies opposite, and coastward from, the BFZ segment of greatest vertical displacement, from Austin southwest to Hondo.

Today, the BFZ is essentially aseismic and widely considered to be dormant. Ewing (2005, 2016) pointed out that Uvalde and related gravels—Late Miocene to Pleistocene outwash fans from the Plateau margins—are not cut by Balcones faults.[1]

The absence of any widespread marine incursion in the otherwise alluvial/interdeltaic coastal-plain Lower Miocene succession of south-central Texas (Galloway, et al, 2011) indicates that net Balcones movement did not involve significant downward displacement of the coastal side of the fault. Accordingly, displacement of the upthrown block was not just *relatively* up—it must have been absolutely up relative to Miocene sea-level (Rose, 2016).

Three lines of evidence suggest that Balcones faulting and the regional uplift of the Edwards Plateau was the terminal, not the initiating event for the Plateau uplift.

(1) The presence of alluvial-deltaic and coastal-interdeltaic terrigenous clastic sediments in the middle Paleocene lower Wilcox Group, lying only about 20 mi coastward (southeast) of the BFZ (Rose, 2016), would seem to mandate that upper Cretaceous strata overlying the Edwards carbonate mass to the west were already elevated above Middle Paleocene sea-level at that time, hence exposed to subaerial weathering and erosion;

(2) Such subaerial erosion could only have intensified gradually during the rest of the Paleocene, all of the Eocene, and into the early Oligocene, as a consequence of the steady regional coastward regression that characterizes Gulf Coast deposition during the ~40 Myr that preceded Balcones faulting;

(3) The presence of scattered sedimentary particles of Upper Cretaceous chalk in terrigenous clastic Eocene formations indicates erosion of Upper Cretaceous formations adjacent to and across the future BFZ.

However, this does not mean that all upthrown faulting along the BFZ was instantaneous at 21 Ma; neither does it preclude some subsequent regional uplift in the area between the BFZ and the Llano Uplift, as suggested by the late-stage Medina Arch (Rose, 1972, 2016) centered around Real County. Maxwell's (1970) discovery of Precambrian pebbles in the late Miocene–Pliocene Goliad Formation at Goliad shows that the ancestral Colorado River had already cut down into the Precambrian of the Llano Dome by 14 to 5.6 Ma, Ewing's (2005, 2016) observation that Balcones-system faults do not cut upper Miocene to lower Pleistocene Uvalde gravel beds, and the well-established present aseismicity of the BFZ all suggest that Balcones faulting was of relatively short duration.

Edwards Plateau

Restored structural mapping on top of the Edwards and associated limestones (Fig. 5) allows integration of surface and subsurface mapping throughout the region. Where erosion in the eastern Edwards Plateau and Hill Country has removed parts or all of the upper Edwards, the original thickness has been restored by adding Edwards isopachous values (derived from the subsurface and from the central and western parts of the Edwards Plateau, where the complete Edwards section is present) to the base Edwards of Rose (1972, 2004), as shown on Figure 7. This mapped surface approximates the surface of the Edwards Plateau at the end of Balcones faulting and uplift. Northwest of the Llano Uplift, the base of the Edwards rises gently (~10 ft/mi) but steadily toward the northwest, reflecting regional Miocene/Pliocene uplift of the Colorado Plateau (Galloway et al, 2011; Ewing, 2016). This is the same configuration observed in the eastward-sloping Ogallala Formation of the High Plains (Llano Estacado), believed to have formed at the same time (Ewing, 1991). The previously noted zone of steepening dip on the east and south sides of the Llano Uplift—the BOD—is still present at the top Edwards mapping horizon

Two structural closures on top Edwards are apparent adjacent to the Llano Uplift: a small feature in northwestern Kimble County which may be a shallow manifestation of deeper Paleozoic faulting, and a more significant feature, a broad northeast-southwest anticline across southern Edwards, northern Real, central Kerr, western Bandera and southwestern Gillespie counties, with vertical closure of more than 250 ft. This is the Medina Arch of Rose (1972, 2016), which also forms the southwestern end of Ewing's (2005) Llano Arch. Paleostructural analysis suggests that the Medina Arch is a late-stage feature related to Balcones faulting.

REGIONAL DISTRIBUTION OF EDWARDS GROUP

Over most of the region covered by this report, the Edwards Group, consisting of two shallow-shelf carbonate depositional cycles, the Fort Terrett and Segovia formations (Rose, 1972, 2017), forms a stratigraphically consistent wedge of shallow-

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[1] The U.S. Geological Survey assigns the Uvalde to the Pliocene. Ewing (2016) implied the Uvalde may be as old as late Miocene.

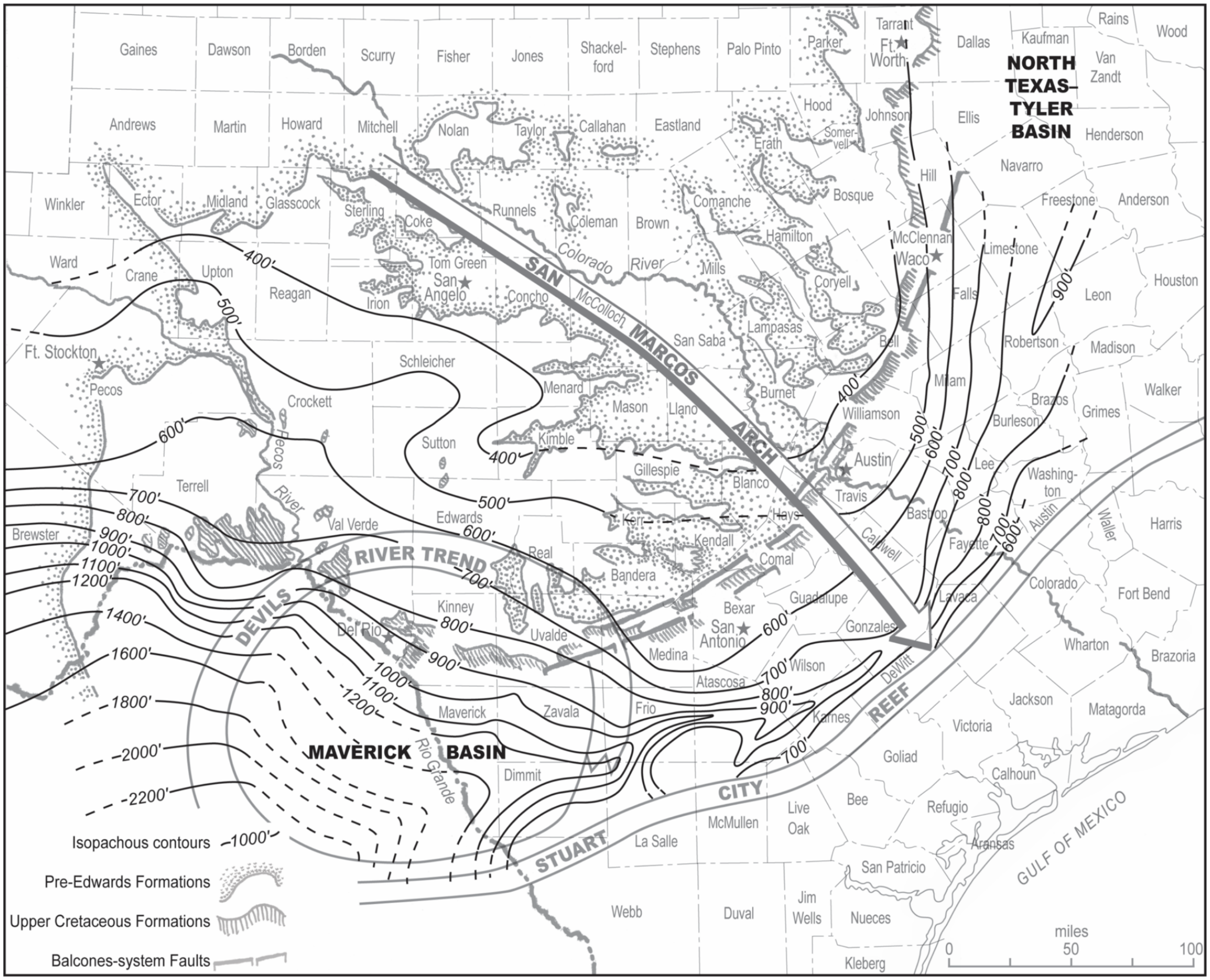

Figure 7. Regional isopach map of Edwards Group and equivalents (Lower Cretaceous) (from Rose, 2016).

shelf carbonate strata that thickens southwestward from about 350 ft on the north edge of the Edwards Plateau to about 600 ft approaching the southern margin (Fig. 7). Here the Edwards Group grades laterally into a narrow belt of massive, bioclastic shelf-margin limestone, the Devils River Formation, that is about 600 to 800 ft thick. Southward, the Devils River grades laterally into three formations representing deposition in the Maverick Basin, an Albian shelf-basin facies: the West Nueces, McKnight, and Salmon Peak formations (Lozo and Smith, 1964; Smith et al., 2000; Smith, 2004). All these formations are considered to be part of the Edwards Group.

To the northeast approaching the south flank of the East Texas Basin, in the area of the Lampasas Cut Plain, the lower part of the Fort Terrett Formation grades into open-marine marls of the Walnut and Comanche Peak formations. These formations also are considered as part of the Edwards Group. Thus the Edwards Group, as defined, serves as a ubiquitous, resistant, consistent, readily identifiable stratigraphic unit, ideal for use as a marker indicating the lateral progress of stream dissection and landscape evolution in the 20 Myr since Balcones faulting began.

Regional Exposure of Top Edwards Surface Pre-Balcones Faulting

Rose (2016) showed that, in the area of the present Edwards Plateau, sedimentary cover above the Edwards Group never exceeded about 1000 ft (to the west) and about 3000 ft (to the east). Gradually intensifying uplift with attendant subaerial erosion, during latest Cretaceous, Paleocene, Eocene and early Oligocene had removed most or all of this sedimentary cover by the time of Balcones faulting, leaving the resistant Edwards Limestone exposed across most of the region. Several primary precursor streams traversed this resistant top-Edwards surface before Balcones faulting and uplift, e.g., the Rio Grande, Pecos, and Colorado rivers. It is also likely that other secondary precursor streams, such as the Concho, Llano, Guadalupe, and Devils rivers, also began to cut down into the exposed thick limestone ter-

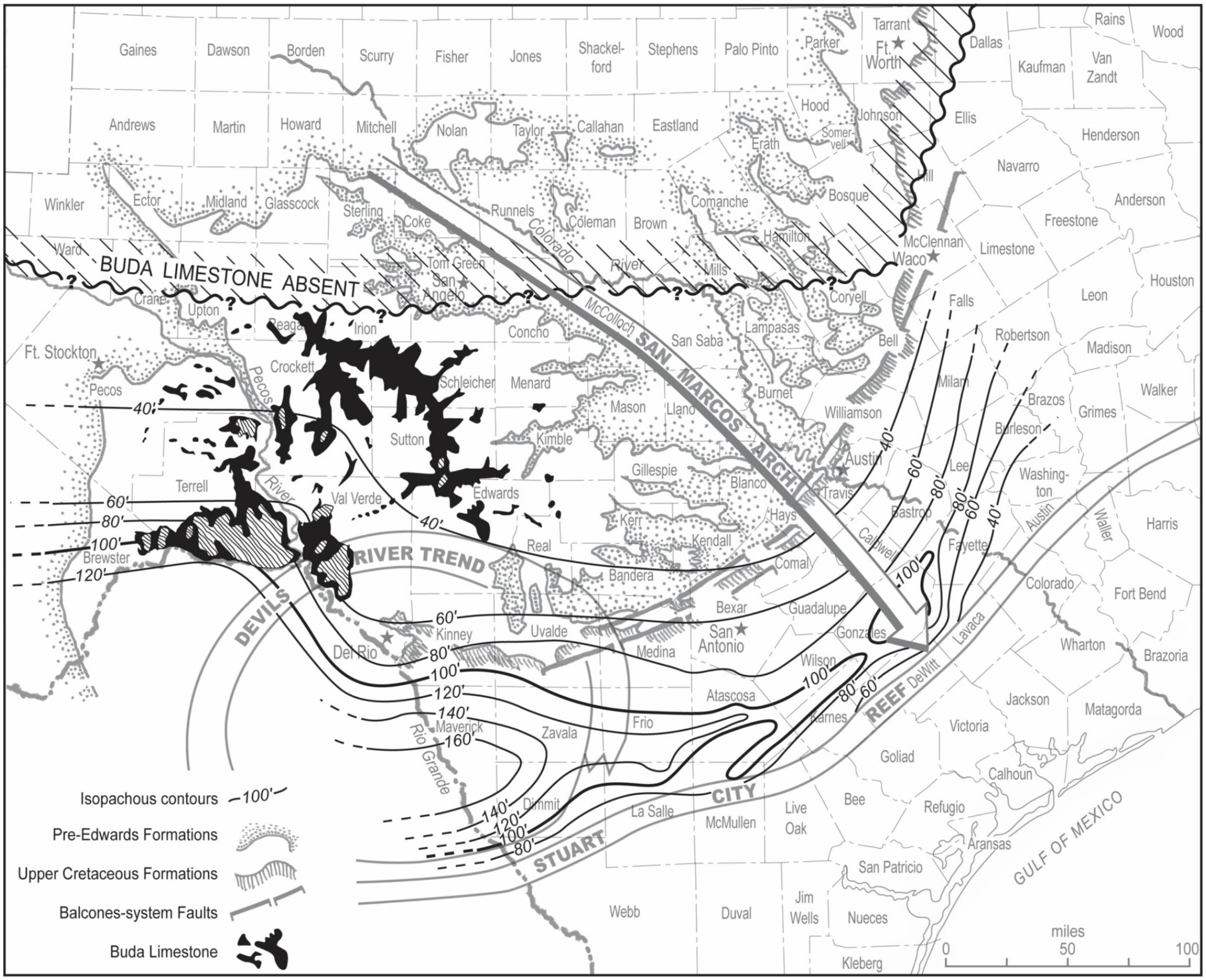

Figure 8. Outcrop areas of thin remnant Del Rio/Buda/Eagle Ford succession, (<50 ft) sequence resting disconformably on the Edwards Group on crest of Edwards Plateau (from Rose, 2016).

ranes, following their previous stream courses, wherever those courses may have been located.

Post-Edwards Remnant Formations on Edwards Plateau

In the center of the broad western sector of the Edwards Plateau, thin remnant patches of post-Edwards (e.g., Cenomanian) formations are preserved (Fig. 8):

1. On the Plateau's southern flank, the Del Rio Formation (0–10 ft) pinches out northwardly between top Edwards and the thin (<20 ft) Buda Limestone.
2. In the western Plateau, Buda Limestone is present as thin (<30 ft), scattered, deeply weathered outliers preserved on topographic highs; no Buda outcrops are found north of the middle fork of the Concho River.
3. Thin (<20 ft) patches of deeply weathered Boquillas siltstone (Eagle Ford equivalent) are preserved in the central, highest parts of some Buda outliers.

On the southwestern flank of the Edwards Plateau, adjacent to the Rio Grande and Pecos rivers, are remnant outcrops of northward-thinning Austin Chalk; erosional truncation at the top precludes determination of true depositional thickness, but the Austin was at least 200 ft thick at that location. At Austin, truncated Austin Chalk outcrops are present within about a mile of the Mount Bonnell Fault; regional isopachous mapping indicate the Austin Chalk is about 350 ft thick at Austin, on the downthrown side of the Balcones Fault (Rose, 2016). Counterpart wedges of Austin and Taylor-Navarro strata may also have been present a few miles inboard from the BFZ between Austin and San Antonio.

It is likely that scattered thin remnants of the Del Rio, Buda, and Eagle Ford (=Boquillas) formations still remained on top of the Edwards in the eastern sector of the Edwards Plateau immediately following Balcones faulting. They can safely be disregarded as being volumetrically inconsequential compared to the thick, resistant Edwards Limestone on which they rest. Furthermore, there is now no way of knowing where such remnants might have been located as the landscape evolved during the last ~20 Myr.

Outcrops of Edwards Limestone and Older Formations in River Valleys

Neogene erosion of the eastern Edwards Plateau region, following Balcones faulting and uplift, has, by the present day, stripped away much of the Edwards Group from valleys of streams that head in the Edwards Plateau, then flow eastward and southward across Trinity-age Glen Rose and Hensel formations, leaving only Edwards remnants in high-standing interfluvial divides. However, in the valleys of the Colorado River and its east-flowing tributaries (the Pedernales, Llano, and San Saba rivers), erosion has cut farther down, into Paleozoic and Precambrian rocks of the Llano Uplift. Farther north, the valleys of Pecan Bayou and Concho rivers have cut down into upper Paleozoic strata. However, prior to Balcones faulting, a continuous blanket of Edwards (and Buda) strata covered the entire Central Texas Platform (Hill and Vaughan, 1898; Woodruff, 1992). The Jollyville Plateau, adjoining Austin on the northwest, is a remnant of that original continuous plateau which has survived erosion by streams of the Colorado River watershed. Rivers draining the southern margins of the Edwards Plateau have cut no deeper than Edwards or upper Glen Rose strata.

STREAM DRAINAGE PATTERNS, EDWARDS PLATEAU AND ADJACENT AREAS

The regional map (Fig. 9), compiled from 34 contiguous 1:100,000 scale topographic quadrangles (U.S. Geological Survey [USGS], 1985–1994), show stream drainage patterns of the Edwards Plateau, Llano Uplift, Hill Country, Lampasas Cut Plain, BFZ, and adjoining areas of the upper Gulf Coastal Plain in relation to faults within the BFZ, and to the outline of the Llano Dome is critical to understanding the evolution of the Edwards Plateau drainage. Digital Plate 1 is the same map presented at more workable scale, accessible electronically.

Drainage basins of the 6 main rivers (Rio Grande, Nueces, Medina–San Antonio, Guadalupe, Colorado, and Brazos) are designated by color. Excluding the major trunk rivers (Rio Grande, Pecos, Colorado, and Brazos) the largest drainage basin within the map area is that of the Concho River (~9000 mi^2), followed by the Devils and Llano rivers, each ~4000 mi^2. The smallest is Cherokee Creek (200 mi^2).

The regional ground-water table of the Edwards Plateau aquifer is the source, as headwater-springs, of the base flow of all rivers that emanate from the Edwards Plateau. On a regional scale, therefore, the drainage pattern of Edwards Plateau rivers is radial (Fig. 9). On the smaller scale of individual river drainage basins, the prevailing drainage pattern is dendritic, commonly elongated where streams are flowing in the same direction as consistently dipping strata over which they flow, such as the Concho, San Saba, Llano, Pedernales, and Devils rivers. Note that the Pedernales River adheres closely to the southern margin of the Llano Dome. Examples of trellis or rectangular drainages are rare, even in the structurally complex terranes of the Llano Uplift. In the BFZ, however, there are many examples of abrupt stream-course changes likely related to faulting (Woodruff, 1977; Woodruff and Abbott 1979, 1986).

Incised Meanders

Distribution

Many rivers and their tributaries in the eastern, southeastern and southern parts of the Edwards Plateau display deeply incised meanders (Fig. 9; Digital Plate 1) (where streams are running in wider valleys, only meandering valleys have significance in this regard). Incised meanders of streams and valleys are notably absent along the northern and western margins of the Plateau. Regionally, deeply incised stream meanders are concentrated adjacent to the BFZ, on the upthrown block, as shown on Figure 10.

Origin

Generally, meanders form in low gradient streams that are running in unindurated sediments or easily eroded bedrock (Leopold and Wolman, 1960; Langbein and Leopold, 1966). Incision occurs during uplift, when a meandering stream cuts down through unconsolidated material into harder underlying bedrock. Implicitly, for the meanders inherited from an earlier, higher stream to be preserved, the underlying bedrock must be laterally homogeneous. In other words, any folds, faults, or fractures in the harder underlying bedrock would be expected to divert the meanders in response to such structural controls.

Time of Meander Formation and Incision

The location and character of surface sediments and formations lying above the buried Edwards carbonate mass thus offer tantalizing, independent evidence as to when they became emergent, and what formations those precursor streams were flowing across when they began to meander. Throughout most of the Plateau area, Glen Rose, Edwards, and Buda carbonate strata are laterally consistent, but vertically variable, whereas older rocks of the Llano Uplift show marked lateral variations, from complex structures as well as lateral lithologic variations, such as igneous intrusions. Hence, the origin of incised meanders in the Llano Uplift may be considered non-diagnostic, as should incised meanders within the BFZ, because of possible fault-deflection. Also, in trying to understand the time and setting in which meandering streams became incised in hard Lower Cretaceous limestone, we must ask, “When was the area of the future Edwards Plateau a low-lying land mass with low gradient streams flowing across soft substrates into adjacent shallow seas?” A related, essential second question must be, “What formations younger than Buda qualify as ‘unindurated’ or very soft, easily eroded material?”

Rose (2016) reviewed the burial history of the area where incised meanders are now present, around the eastern and southern periphery of the Edwards Plateau, identifying soft candidate formations that may have been positioned above the old Edwards carbonate bank north and west of the BOD, and which may have been exposed in a low gradient coastal landscape. Sediments in formations younger than early Paleocene would seem to be disqualified, inasmuch as terrestrial terrains in which they were deposited sloped more strongly coastward, reflecting gradually accelerating uplift, as previously discussed. Whatever its late Cretaceous history of alternating immersion and subaerial erosion may have been, the area above the old Comanchean carbonate mass, with whatever veneer of Upper Cretaceous formations remained to cover it, was finally exposed beginning in the middle Paleocene. It may be visualized as a slightly elevated upland bordered on the northeast, southeast, and southwest by a flat coastal plain made up of terrigenous clastic sediments, traversed by rivers that headed far to the west and northwest (Galloway et al., 2011). Meandering streams existed on its southeastern, southern, and southwestern flanks; such streams had probably already begun to cut down into the underlying sedimentary cover, eventually to entrench themselves during Balcones uplift. Rose (2016) suggested the most likely origin of the incised meanders was lower Paleocene (Midway) mudrocks, exposed just before middle Paleocene Lower Wilcox terrestrial clastic deposition began. Thus meanders which formed in soft, weathered Midway mudstones were incised by Lower Wilcox streams, and perpetuated downward, as gentle uplift began to elevate the area, and Ewing (2016) agreed. It is significant that the arcuate belt of incised meanders (Fig. 10) coincides with the

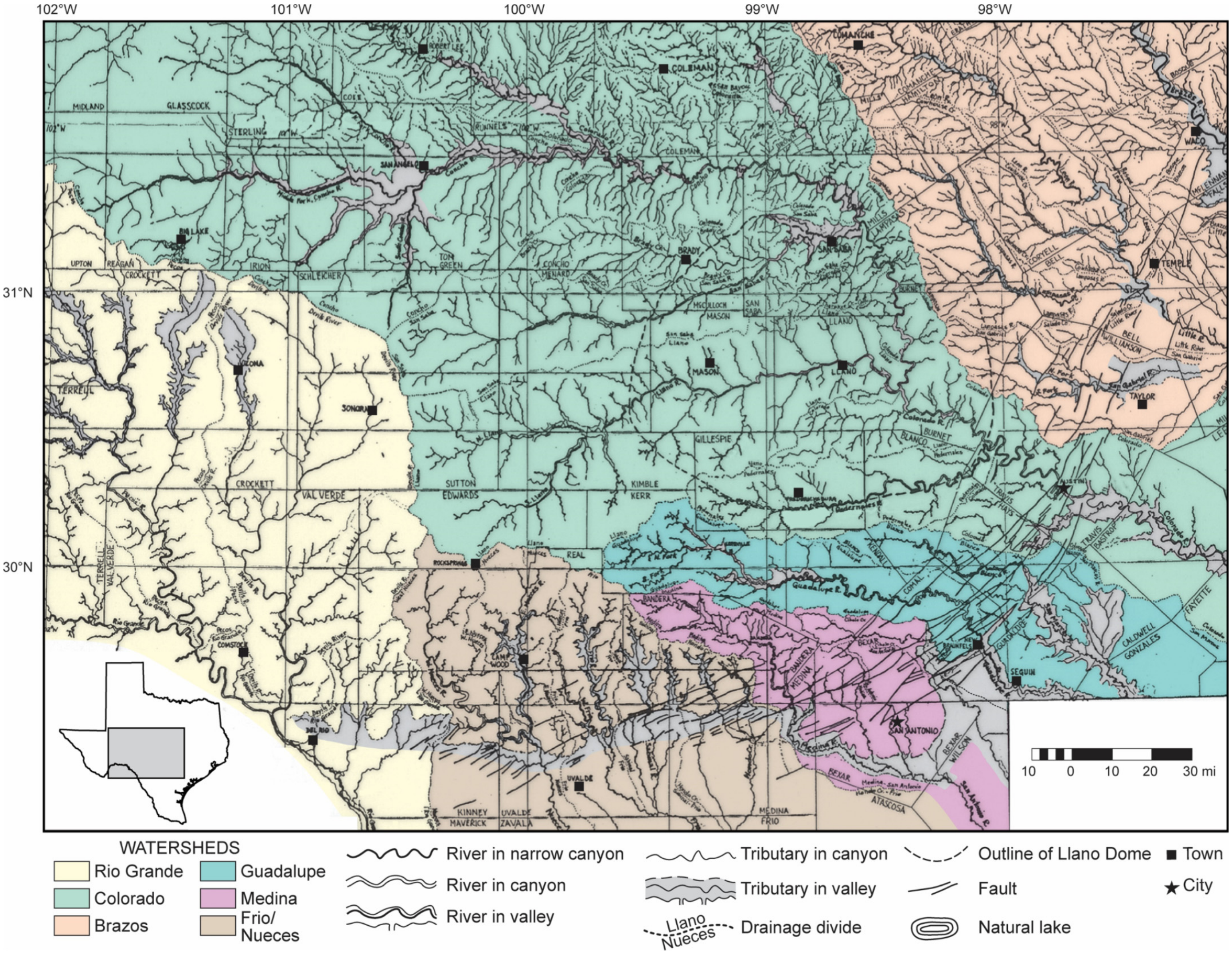

Figure 9. Map showing drainage basins of Central Texas rivers.

projected pinchout of the Midway Clay along the margins of the Edwards Plateau (Rose, 2016).

Examples of Incised Meanders

Depth of incision of the Rio Grande ranges from about 300 ft near the mouth of the Devils and Pecos rivers to nearly 600 ft in eastern Terrell County. The dramatic, large-amplitude incised meanders of the Rio Grande, lower Pecos, and lower Devils rivers in Val Verde County, near Comstock (Fig. 11A), suggest a large (width and volume) stream system, perhaps twice as large as the ancestral Colorado River (Fig. 11B), which is incised to a depth of about 575 ft a few miles west of Austin. Considering that the amplitudes of modern Colorado River meanders southeast of Austin are slightly smaller than the entrenched Colorado River upstream (northwest) from the BFZ, a reasonable conclusion is that the ancestral Colorado River may have been somewhat larger than the present Colorado.

Depth of incision of the Guadalupe River ranges from about 475 ft in the vicinity of Canyon Dam to about 300 ft near Sisterdale, about 40 mi west. Based on the amplitude of entrenched meanders, it is also clear that the ancestral Guadalupe River (Fig. 12A) was a smaller stream than the ancestral Colorado, and much smaller than the ancestral Rio Grande, lower Pecos, and lower Devils rivers. By similar reasoning, the ancestral Guadalupe River upstream from New Braunfels may have been a somewhat larger stream than its modern counterpart downstream from New Braunfels. Depth of incision varies on the upper reaches of the Guadalupe (350 ft), North Medina (425 ft), Sabinal (525 ft), Frio (675 ft), and East Nueces (560 ft) rivers. Lower-amplitude incised meanders on those streams (Fig. 12B) are consistent with somewhat larger stream flows than their current counterparts.

Colorado River Anomalies

Great Bend of the Colorado River

Dr. Charles M. Woodruff, Jr. (1992, personal communication) pointed out two anomalous drainage patterns of the Colorado River in Central Texas. The first anomaly has to do with the Great Bend of the Colorado River (Fig. 13). Upstream from its juncture with the Concho River in northern Concho County, the Colorado maintains a consistent northwest-southeast course. Below the mouth of the Concho however, the Colorado runs eastward, southeastward, then southward, before resuming its regional southeasterly flow roughly 100 mi downstream, about 10 mi below the mouth of the Llano River. This great bend seems to be related to the underlying northeastern quadrant of the Llano Dome (Fig. 14), indicating a northeasterly shift in the river's course in response to northeast regional dip that existed on top of hard carbonate strata of the Pennsylvanian Marble Falls For-

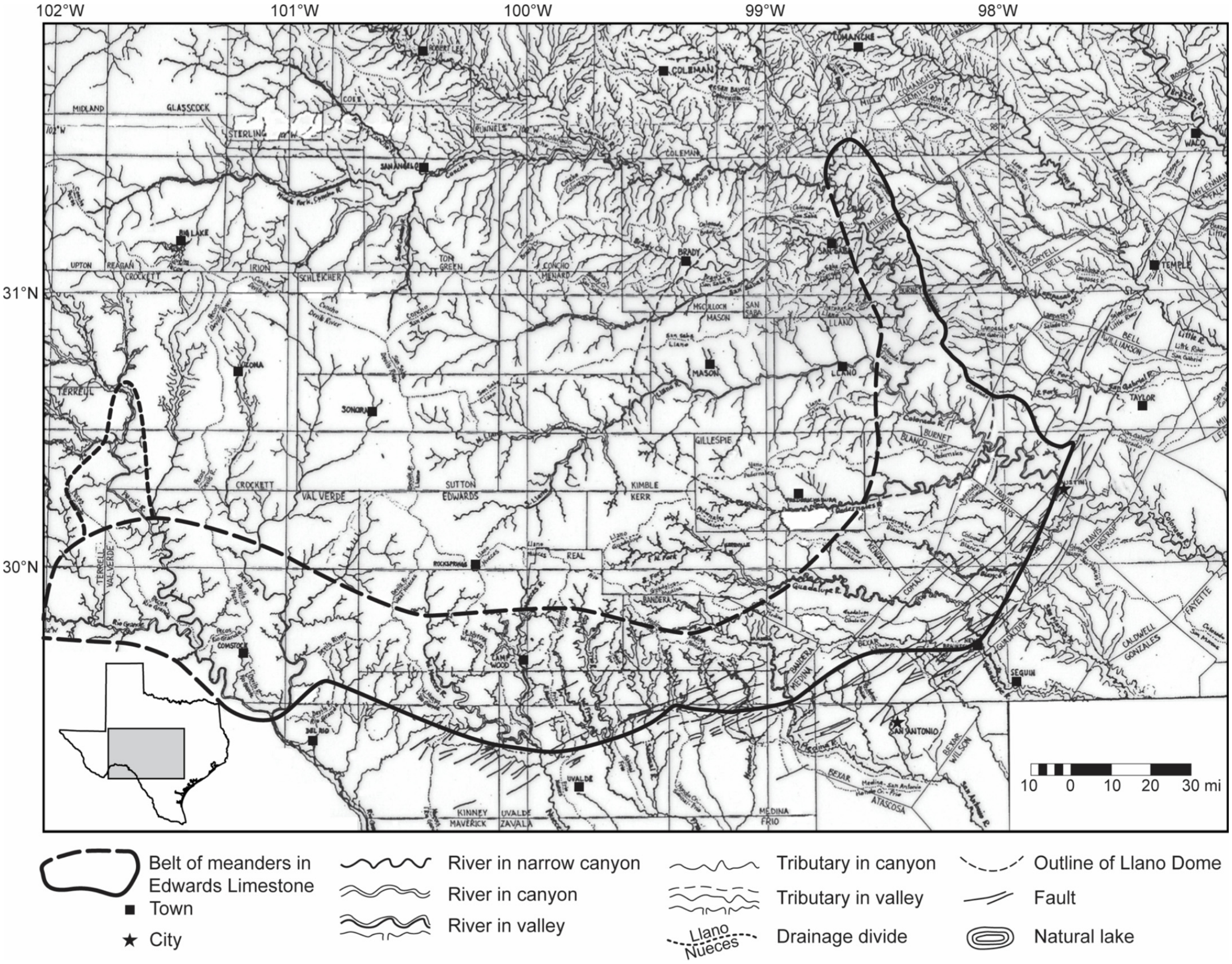

Figure 10. Belt of incised meanders of rivers and streams on Edwards Plateau.

mation. As will be shown later, the Colorado River and its tributaries had cut downward into these older strata by 14 to 10.5 Ma. Although the Colorado River now runs in Lower Paleozoic or Precambrian rocks in its great bend, it seems likely that the river may have started its northeastward shift across the resistant, east-dipping, gently sloping surface of the exposed Edwards Limestone, or other resistant underlying Lower Cretaceous formations, before cutting downward into the underlying, increasingly resistant, Paleozoic strata. Finally, the present position of the Colorado River, adjacent to the eastward-steepening homocline of the BOD along the boundary between Llano and Burnet counties, lies in the outcrop area of extremely resistant Precambrian granite and gneiss, making further eastward shifts more difficult.

An alternative, or perhaps ancillary, explanation for this shift involves the invocation of stream piracy, wherein a hypothesized west-reaching tributary of the Pecan Bayou precursor stream, cutting headward (west), intersected and captured the Colorado River, diverting it into the valley of the Pecan Bayou precursor. Increasingly steepening eastward dip (thus subsidence) may have depressed strata along the precursor course of Pecan Bayou, thus producing the steeper stream gradient necessary for piracy to take place (Figs. 4 and 5).

Asymmetric Tributaries

The second anomaly has to do with the marked asymmetry of the Colorado River's tributary system: from its junction with the Concho River 150 mi southeastward to Austin. Major east-flowing tributaries, such as the Concho, San Saba, Llano, and Pedernales rivers, are all long (70–130 mi), relatively straight, east-flowing streams, whereas all west-flowing tributaries are very short, less than 15 mi long (Fig. 13). This supports the hypothesis that, after Balcones faulting and regional uplift, the Colorado River gradually shifted course to the northeast, migrating laterally more than 40 mi, consuming its eastern tributaries and forcing its western tributaries to extend themselves eastwardly. It may also be significant that many of the Colorado River's short eastern tributary streams, such as Morgan Creek in Burnet County, appear to be truncated upper dendritic segments of once-longer streams.

Asymmetric tributaries are also present in drainage basins of the Lampasas Cut Plain: Cowhouse Creek, Lampasas River, and both forks of the San Gabriel River all appear to have shifted northeastward, in response to the prevailing northeast dip of Edwards Group strata (Digital Plate 1).

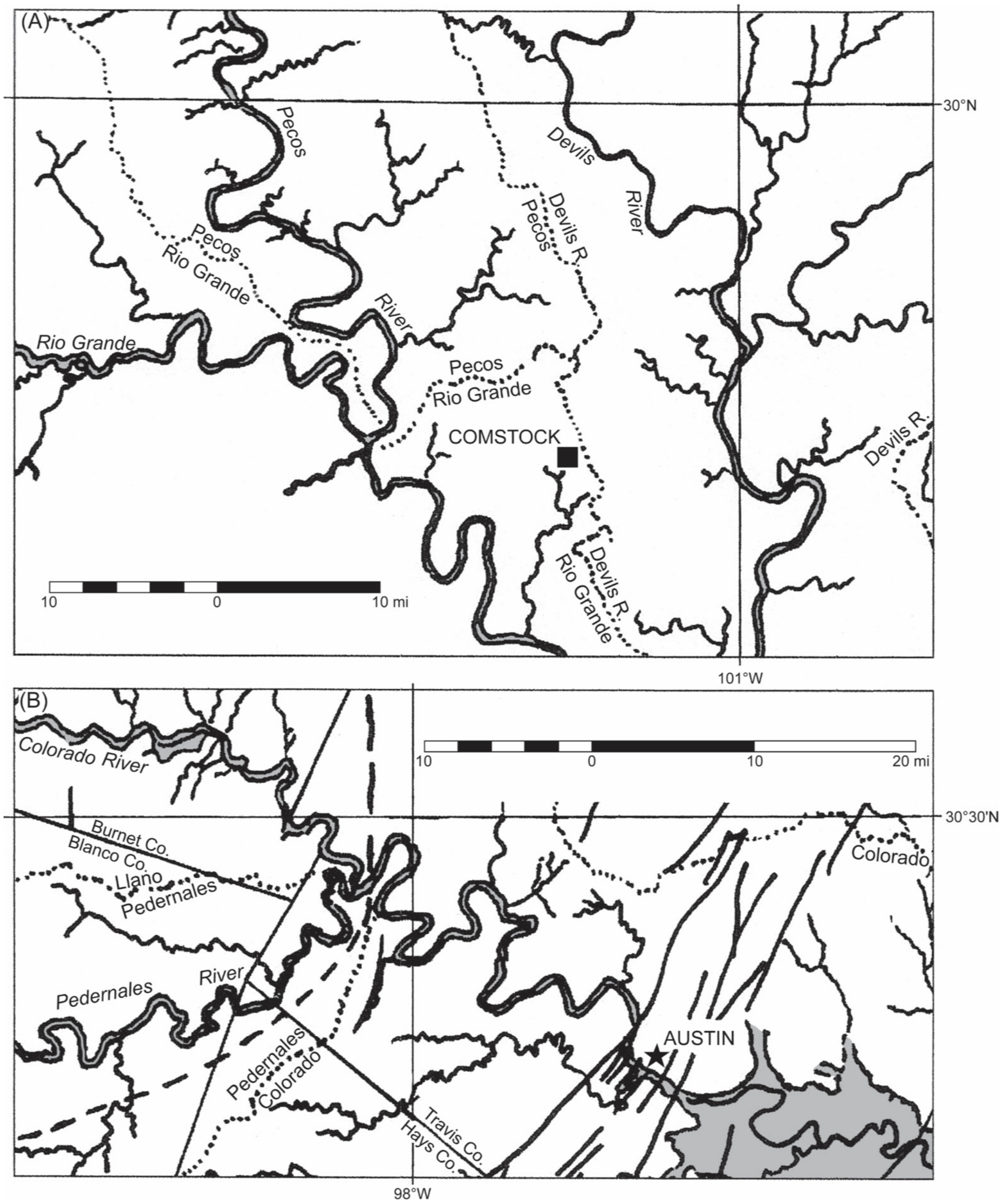

Figure 11. Examples of large-scale incised meanders, Edwards Plateau. (A) Incised meanders of Rio Grande, Pecos, and Devils rivers, western Val Verde and eastern Terrell counties. (B) Incised meanders of Colorado and Pedernales rivers, Burnet, Blanco, Hays, and western Travis counties.

Stream Piracy

Woodruff (1977) and Woodruff and Abbott (1979, 1986), have pointed out examples of stream piracy, where the Medina, Guadalupe and Blanco rivers, and Cibolo Creek (whose courses across the eastern Edwards Plateau are south-southeasterly), divert sharply southward so as to cross the BFZ orthogonal to the general trend of Balcones faulting. These streams then resume their southeasterly courses across the upper Gulf Coastal Plain toward the Gulf of Mexico (Fig. 9; Digital Plate 1). Grimshaw and Woodruff (1986, p. 74–75) showed that “transfer zones in Balcones en echelon fault systems may also have caused diversion of Miocene streams and consequential stream piracy.”

According to Woodruff and Abbott (1986, p. 79), “stream piracy occurred...as a result of streams with steeper gradients eroding normal to the BFZ capturing headwater streams. Associated with these abrupt elbow turns is incision into steep-walled canyons within the resistant limestone.” Woodruff and Abbott (1986, p. 78) suggested that such stream piracy began in early Miocene, because the Plateau was already elevated above the adjacent coastal plain, perhaps as early as “about the end of the Cretaceous.”

The prominent incised meanders in the upper reaches of the Medina, Guadalupe, and Blanco rivers must therefore have already existed before late Oligocene or early Miocene time. By extension, analogous incised meanders on the upper reaches of counterpart streams in the Edwards Plateau also probably existed at the same time. Stream diversions such as those described in the Blanco, Guadalupe, Cibolo, and Medina drainages are absent in rivers farther west (the Frio and Nueces systems), whose southward courses across the southern margins of the Plateau already allowed them to cross the BFZ orthogonally, before then deflecting southeasterly across the coastal plain of the Rio Grande Embayment (Fig. 9; Digital Plate 1).

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[2] Colorado, Concho, San Saba, Llano, Pedernales, Blanco, Guadalupe, Medina, Frio, East Nueces, West Nueces, and Devils rivers.

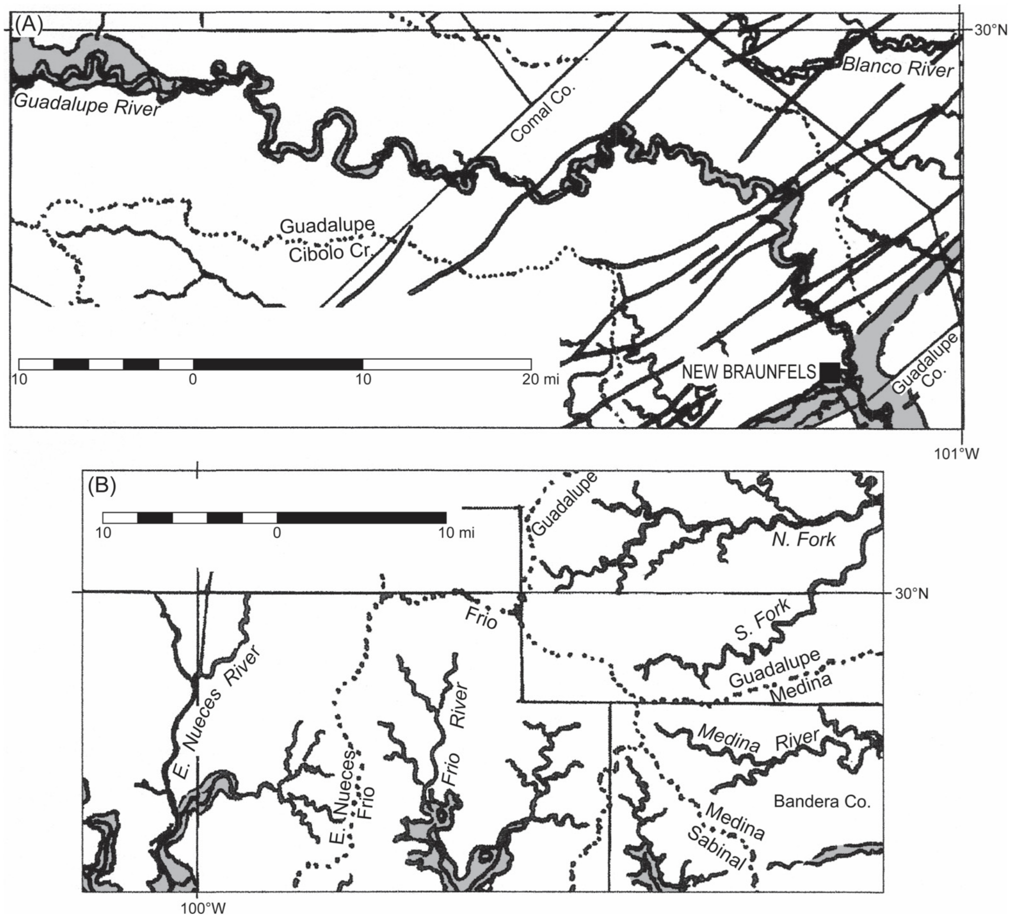

Figure 12. Examples of small-scale incised meanders, Edwards Plateau. (A) Incised meanders on Guadalupe River, Kendall and Comal counties; (B) Incised meanders on upper reaches of East Nueces, Frio, Medina, and Guadalupe rivers, Real, Bandera, and Kerr counties.

STREAM PROFILES OF RIVERS ORIGINATING IN THE EDWARDS PLATEAU

Stream profiles of twelve rivers[2] were constructed to:

(1) identify and interpret different profile-patterns, and
(2) relate stream profiles to the geologic formations of their host valleys, which was essential to delineate the sequential erosional retreat of the base (bKed) and top (tKed) of the Edwards Limestone since the onset of Balcones faulting.

Methodology

The twelve profiles are shown on Digital Plate 2, a plate that is too large to appear in this article; consequently, it is made available electronically. The Guadalupe River profile is included herein, however, to illustrate and help explain how stream profiles were utilized in subsequent analysis of landscape evolution (Fig. 15). Each profile runs from the highest point of its drainage (where it usually is intermittent, not a permanent stream) downstream to its intersection with another river, or across the BFZ and out onto the coastal plain. Intersections of each stream valley with crossing topographic contours (50 ft and 100 ft contours) were utilized in plotting the stream profile. Formation boundaries such as top Edwards (tKed), base Edwards (bKed), and base Cretaceous (bK) were noted on each profile, as were the mapped traces of all faults within the BFZ that crossed each stream. Intersections of rivers with tributary streams were also posted, as well as county lines, adjacent towns, and major dams.

Stages 1 to 6 on Stream Profiles

In order to map the stages of erosional removal following the onset of Balcones faulting, the vertical interval of rock above each stream profile was subdivided into 6 stages of equal thickness (as shown on the Guadalupe River profile [Fig. 15]). For the purpose of modeling the slope-retreat of the Edwards Plateau, it is assumed that Balcones faulting began 21 Ma, and that the rate of vertical removal by erosion was consistent through the following 21 Myr to the present time.[3] This leads to the identification of 6 stages, each lasting 3.5 Myr:

Stage 1: 21–17.5 Ma
Stage 2: 17.5–14 Ma
Stage 3: 14–10.5 Ma
Stage 4: 10.5–7.0 Ma
Stage 5: 7–3.5 Ma
Stage 6: 3.5 Ma–present time

Figure 15 demonstrates the convex upward profile of the Guadalupe River near its western origin, near the top of the Edwards Plateau. It is essential that the reader keep clearly in mind

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[3] This assumption is required in order to model the successive stages of slope retreat. The writer recognizes that erosion-rate in the region probably varied during the 21 Myr after Balcones faulting began, influenced by three undocumented variables: (a) duration of faulting, (b) rate of uplift, and (c) climatic cycles. However, none of these variables is known well enough to be quantified beyond the equality assumption. Moreover, we do not know how any of these variables would impact the rate of regional volumetric removal of bedrock and sediment.

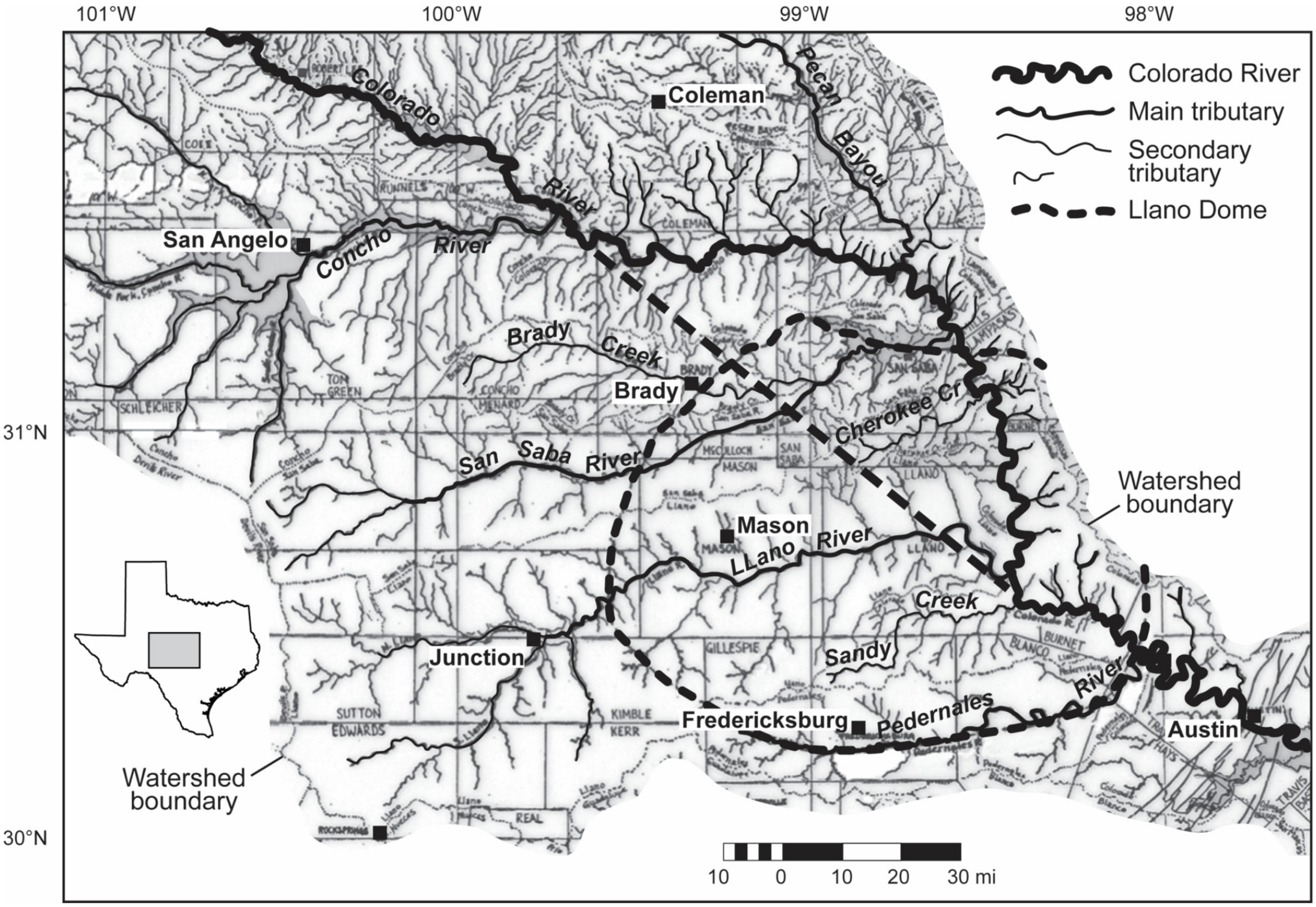

Figure 13. Watershed of Colorado River, Central Texas, showing Great Bend of Colorado, and asymmetric tributary system (western tributaries elongated, eastern tributaries truncated).

that these 6 stages are not stratigraphic zones, i.e., *sequentially deposited*. Rather they are intervals of rock that were *sequentially removed by processes of weathering, erosion, and dissolution*. stage 6, the most recently removed, is geometrically the lowest stage on the stream profiles, whereas stage 1, the stage of earliest removal, is geometrically the highest on the stream profiles. Figure 15 illustrates this essential distinction: stage 6 is the increment of bedrock that has been most recently removed throughout the Guadalupe River valley. Accordingly, it is important to emphasize that the most recent boundary of every stage lies at its base, not at its top. Further, the top (beginning) of stage 6 is also the base (end) of preceding stage 5. Another way to think about stages 1 to 6 is that the bottom surface of each successive stage in each river valley represents the profile of that stream at the end (not the beginning) of that stage. Figure 16 shows the location of stages 1–6 as they are projected from the profile (Fig. 15) to the map of the Guadalupe River valley. For each of the 12 rivers that head in the Edwards Plateau (Digital Plate 2), the intersections of stages 1–6 with top (tKed) and base (bKed) are indicated by a vertical arrow with a notation showing which surfaces are intersecting (examples: top 5 w/bKed and top 2 w/tKed), as shown on Figure 15.

Types of Profiles

Table 1 provides the basis for classifying the 12 rivers considered in this analysis. Two types of stream profiles are recognized among the 12 river profiles: **concave-upward** and **ramp**. The Pedernales, Blanco, Guadalupe, Medina, Frio, and East Nueces rivers are concave-upward profiles, whereas the Colorado, Concho, San Saba, Llano, West Nueces, and Devils rivers represent ramp profiles.

Concave-upward profiles are associated with shorter, steeper gradient rivers (Guadalupe River [Fig. 15; Digital Plate 2–Profile 7) that lie in the southern and eastern parts of the Edwards Plateau. Their total gradients range from 14.5 ft/mi to 33.1 ft/mi, averaging 21.3 ft/mi. Upstream from where such rivers cross the most upstream fault of the BFZ, their gradients are all steeper, ranging from 18.4 ft/mi to 37.5 ft/mi, averaging 27.6 ft/mi. Ramp profiles are longer, with lower stream gradients, such as the Llano River (Digital Plate 2–Profile 4); their total gradients range from 5.6 ft/mi to 15.7 ft/mi, averaging 10.5 ft/mi. These rivers are located in the western or northern sectors of the Edwards Plateau.

All rivers having concave-upward profiles head in the area of the Medina Arch (Fig. 5), believed to be a post-Balcones anticlinal feature; they all have steeper gradients than area rivers with ramp profiles. The writer believes that, with one notable exception (Devils River), rivers with ramp profiles are older streams, whereas concave-upward rivers are younger streams.

Knickpoints

Short segments of abruptly steepened stream profiles, or "knickpoints," are often associated with a stream encountering much more resistant bedrock. They also occur where upstream

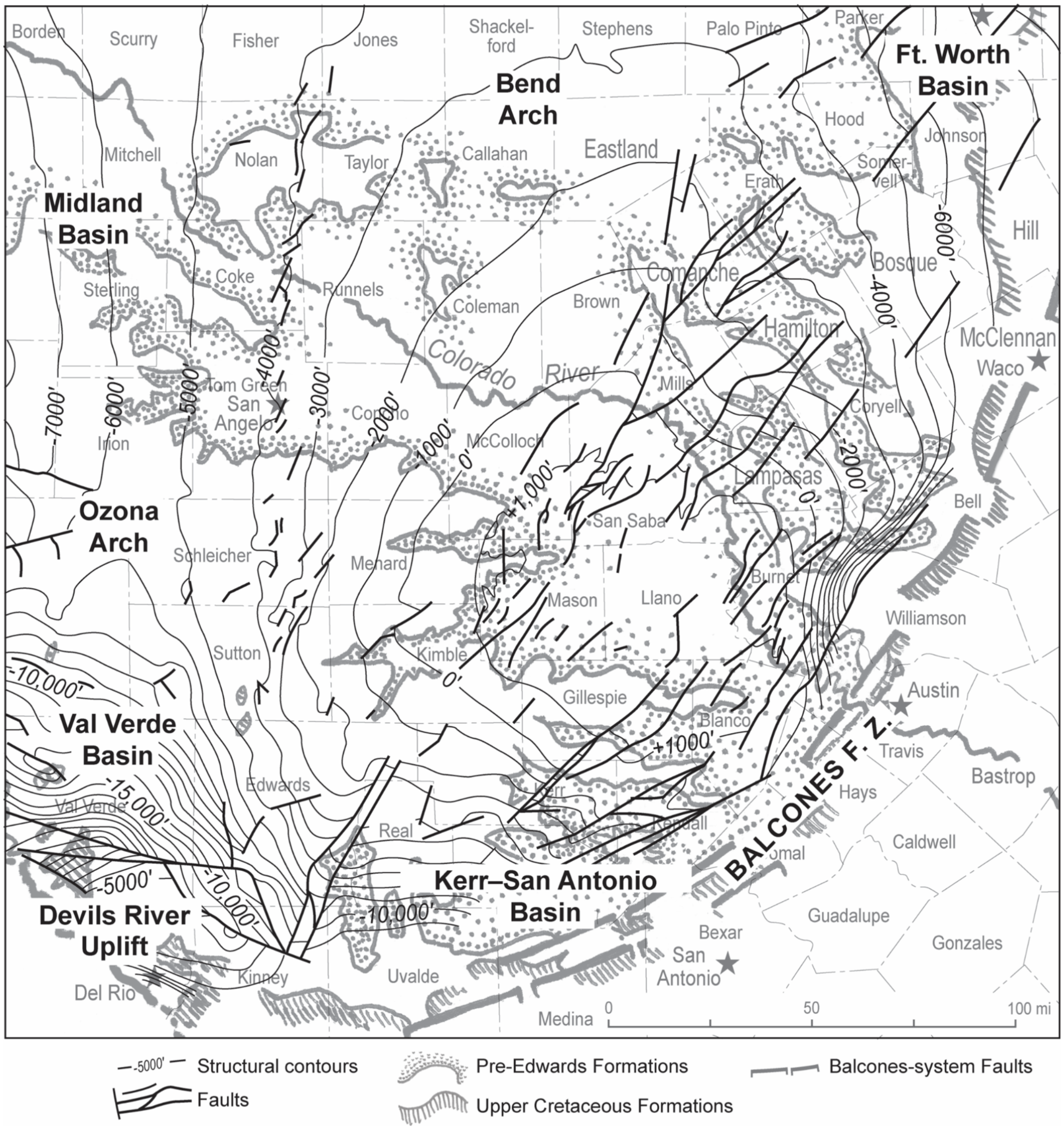

Figure 14. Structure on top of Ellenburger Group (Lower Ordovician, Central Texas) (modified after Ewing, 1991; Rose, 2016).

migration of the stream crosses a fault juxtaposing hard rock against soft rock. Among the 12 river profiles of this report, only the Colorado River profile (Digital Plate 2–Profile 1) displays a knickpoint. It is located about 50 mi upstream from where the river crosses the Mount Bonnell Fault. However, this knickpoint also occurs where the river crosses from Pennsylvanian sedimentary rocks upstream onto a very hard Precambrian granite and gneissic terrane. Intuitively such a lithologic contrast would seem more likely to produce a flattening, not a steepening, of the profile. Accordingly, the Colorado River knickpoint is more likely the result of the upstream migration of the river crossing the Mount Bonnell Fault. The rate of upstream migration is calculated to be 50 mi/21 Myr or about 2.5 mi/Myr.

Effectiveness of Different Agents of Bedrock Removal

Figures 1 and 2 indicate that regional westerly migration of the Edwards Plateau has been accomplished primarily through lateral slope retreat of the Edwards Limestone, caused by headward erosion of streams, and secondarily through vertical removal by weathering, surface dissolution, and erosion. Obviously, the rate of lateral slope retreat has been much faster than the rate of vertical removal. Using the Guadalupe River profile (Fig. 15) as an example, approximately 1100 ft of Edwards and Glen Rose strata have been removed from the river valley on the upthrown block of the first Balcones fault in 21 Myr, for an average of

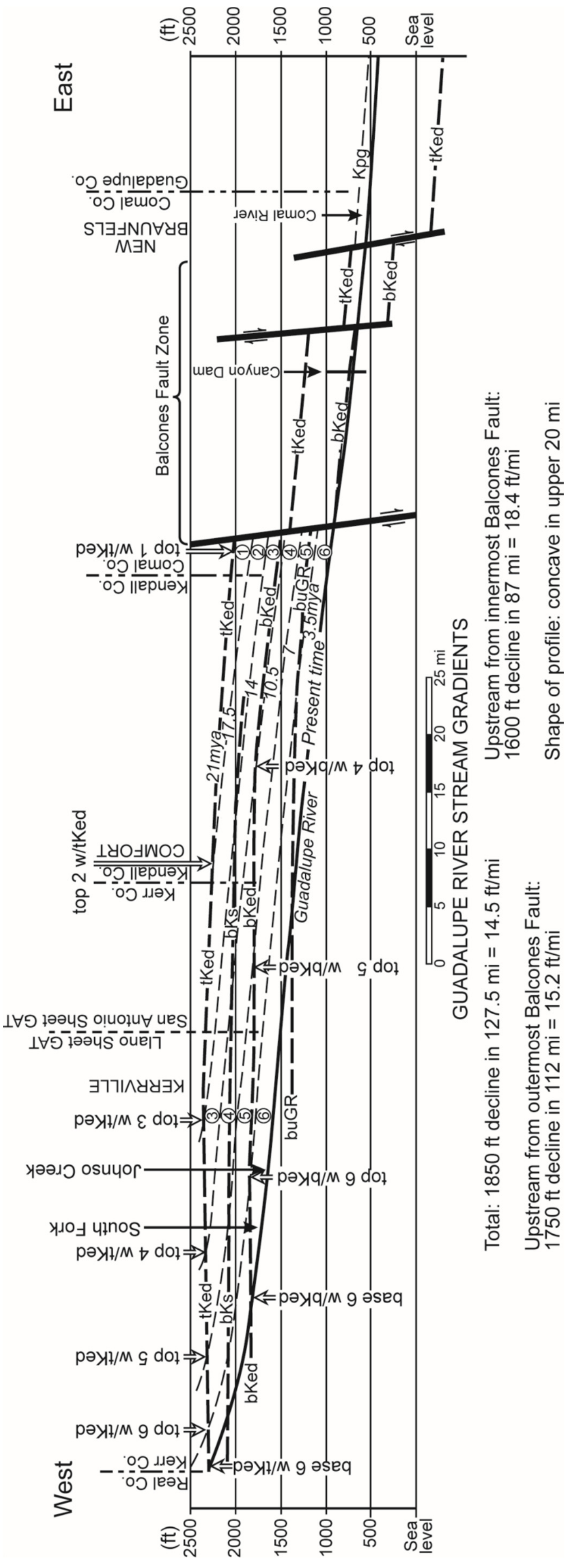

Figure 15. Guadalupe River stream profile, Kerr, Kendall, and Comal counties.

about 50 ft/Myr. Figure 16 shows that, in the Guadalupe River valley, the base of the Edwards (bKed) retreated about 65 mi during the same time, or about 3 mi/Myr.

The relative contribution of *dissolution* of carbonate bedrock, compared with *erosion* is more uncertain, however. Because regional isopach mapping of the Edwards Group (Fig. 7) indicates no noticeable stratigraphic thinning from the Edwards Plateau, across the highly karsted BFZ and into the adjacent subsurface, it appears that dissolution has only caused increased karstic porosity. Thickness of the stratigraphic framework is unaffected which suggests that dissolution *within* the intact stratigraphic sequence may have accounted for perhaps only 10–20% of total rock removal, leaving as evidence increased vuggy and cavernous porosity. However, the characteristic rock-littered (remnant fragments with smoothed, even rounded, outer surfaces) ground surfaces of the flat or gently rolling Edwards Plateau pasturelands, provides mute testimony as to the ubiquity and effectiveness of weathering and erosion at the ground surface, and dissolution may play a large part in such processes.

DEPICTING EDWARDS PLATEAU SLOPE RETREAT AFTER BALCONES FAULTING

This section of the report reviews methodology by which the sequential retreat of the Edwards Limestone westward and northward from the BFZ may be represented. This retreat, proceeding primarily by weathering, headward erosion and dissolution of the thick, resistant Edwards Limestone that forms the steep eastern and southern margins of the Edwards Plateau, began immediately upon the creation of the linear fault scarp fronting the regional uplift that attended Balcones faulting about 21 Ma (early Miocene). This section of the report reviews geological facts, assumptions, and sequential mapping procedures required to produce the map series Fig. 17A–17G, showing the region immediately following first Balcones faulting, followed by 6 stages of slope retreat, concluding with stage 6, which shows the present-day configuration of the eastern and southern margins of the Plateau.

Pertinent Geological Facts

Five geological conditions combine to set the factual framework that allows this analysis to be made:

1. (1) The thick, resistant Edwards Group and overlying thin Del Rio/Buda/Eagle Ford succession were formerly ubiquitous over the entire region between the BFZ and the present margins of the Edwards Plateau (Fig. 2).
2. (2) The top of the Edwards Group forms a simple homocline that dips gently southeastward across the subject area before encountering the BFZ (Fig. 5).
3. (3) The Edwards Group is a well-documented, regional carbonate massif that thickens gradually across the area, southwestward and southeastward (Fig. 7).
4. (4) Regional topography and geology are well-documented across the area (Geological Atlas of Texas [GAT] 1:250:000 map series; Bureau of Economic Geology, 1970–1982), allowing stream profiles to be integrated with geology.
5. (5) Time of Balcones faulting, associated regional uplift and start of regional dissection are known (~21 Ma).

Necessary Assumptions

Six assumptions, all apparently well justified geologically, are necessary for this analysis to proceed with confidence:

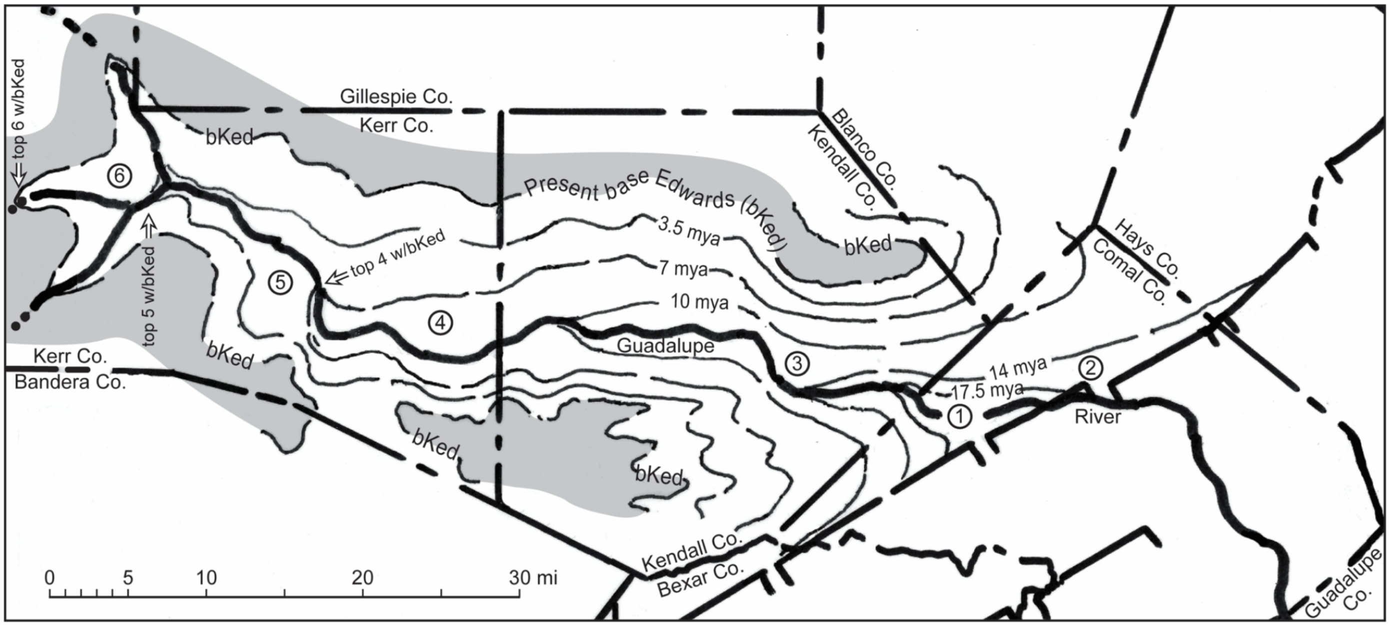

Figure 16. Work map demonstrating procedure for mapping erosional stages 1–6 on Guadalupe River stream profile, Kerr, Kendall, and Comal counties.

(1) Erosion related to subaerial exposure and gentle uplift of the Central Texas Platform during the 37 Myr from middle Paleocene through uppermost Oligocene removed most of the ~1000 to 3000 ft of Upper Cretaceous and lowermost Paleocene sediments covering the Central Texas Platform, leaving the underlying resistant Edwards Group carbonates widely exposed (Rose, 2016) in early Miocene time;

(2) Most of the post-Balcones uplift of the eastern Edwards Plateau, occurred at the time of major Balcones faulting (21 Ma);

(3) Vertical removal rate of Edwards Group and older formations (through weathering, erosion, and dissolution) was roughly consistent throughout the Neogene;

(4) Present stream profiles of area rivers are similar to those of the past;

(5) Inboard-most Balcones faults occurred earliest in the episode of Balcones faulting, and had greatest vertical displacements; all coastward faults are later adjustments (Collins and Woodruff, 2001), but occurred as part of the Balcones faulting episode);

(6) Primary regional river systems predate Balcones faulting as low gradient ancestral streams (Rio Grande, Pecos, Colorado, and Brazos), as shown by Galloway et al. (2011); some secondary rivers may also predate Balcones faulting (Concho, Llano, and Guadalupe) but their ancient courses are unknown.

Construction of Maps

Mapping Base (bKed) and Top (tKed) of Edwards Limestone Outcrop across the Project Area

The complete process of map preparation is illustrated using the Guadalupe River profile (Fig. 15) with the associated work map (Fig. 16) as examples. Please note that the most upstream Balcones faults as well as the present base of Edwards (bKed) have already been plotted on the work map. The reader is reminded that the *geometric base* of each stage on the profile marks the *end* (not the beginning) of that stage.

Within the Guadalupe River basin, intersections of the base of Edwards (bKed) with the bases of stages 6, 5, 4, and 3 were plotted on the work map along the course of the Guadalupe River (see arrows); the bases of stages 2 and 1 are not shown because the ancestral Guadalupe River apparently had not yet cut down that far toward the base of the Edwards (bKed).[4] Because the stages are of equal thickness at any place (although thicknesses may increase or decrease as the total section above the stream profile thickens or thins laterally), and the Edwards Group is near-horizontal, the boundaries of the stages were laterally projected on the map as if they were topographic contours. Each boundary was labelled with its assigned age before present, and each stage was represented by a circled number on the map, stage 6 being most recent, stage 1 representing the 3.5 Myr following the onset of Balcones faulting, 21 Ma.

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[4] This assumes that if there was a pre-Miocene Guadalupe River, it had not cut down into the Edwards Limestone. But if such a stream had already cut downward, say, 100 ft into the Edwards before Balcones faulting, the Guadalupe stream profile would indicate that, by the end of stage 1, the depth of stream erosion was about 100 ft less than it really was. This may be a minor problem for the Guadalupe River, but it is probably a somewhat more serious, if immeasurable, problem for the Colorado River. A second source of uncertainty about the Colorado River's pre-Balcones entrenchment may have to do with the increasing regional southeast dip nearing the Mount Bonnell Fault, which may also mask pre-Balcones entrenchment. In any case, it is here assumed that pre-Balcones entrenchment of the Colorado River did take place, possibly amounting to as much as 100 ft.

Table 1. Properties of Edwards Plateau rivers.

	RIVER	PROFILE TYPE	CROSSES BFZ?	HEADS IN MEDINA ARCH?	STREAM GRADIENTS		COMMENTS
					TOTAL	ABOVE BFZ	
1	Colorado	Ramp	yes	no	1500 ft/267 mi	1350 ft/230 mi	Note knickpoint at
2	Concho	Ramp	no	no	1350 ft/147 mi = 9.2 ft/mi	N/A	Intersects Colorado River at elev. 1490 ft
3	San Saba	Ramp	no	no	1330 ft/123 mi = 10.6 ft/mi	N/A	Intersects Colorado River at elev. 1100 ft
4	Llano	Ramp	no	no	1400 ft/143 mi = 10.1 ft/mi	N/A	Intersects Colorado River at elev. 850 ft
5	Pedernales	Concave Up	no	yes	1550 ft/81 mi = 18.5 ft/mi	N/A	Intersects Colorado River at elev. 650 ft
6	Blanco	Concave Up	yes	yes	1225 ft/37 mi = 33.1 ft/mi	1200 ft/32 mi = 37.3 ft/mi	
7	Guadalupe	Concave Up	yes	yes	1850 ft/127.5 mi = 14.5 ft/mi	1600 ft/87 mi = 18.4 ft/mi	
8	Medina	Concave Up	yes	yes	1950 ft/123 mi = 15.9 ft/mi	1150 ft/47 mi = 24.4 ft/mi	
9	Frio	Concave Up	yes	yes	1800 ft/84 mi = 21.4 ft/mi	1150 ft/42 mi = 27.4 ft/mi	
10	East Nueces	Concave Up	yes	yes	1400 ft/57 mi	1150 ft/38 mi	Intersects W. Nueces River
11	West Nueces	Ramp	no	no	1550 ft/99 mi	850 ft/40 mi	Intersects E. Nueces River
12	Devils	Ramp	no	no	1710 ft/147 mi = 17.6 ft/mi	N/A	Intersects Rio Grande River at elev. 1000 ft

This procedure was utilized to map each of the 12 basins analyzed. The boundaries of the respective stages then were joined along the boundaries of the respective drainage basins to generate a single map showing the location of the base of the Edwards Limestone (bKed) at the end of each of the 6 stages, throughout the entire project area. The primary advantage of posting all stages on a single work map is to reconcile the distribution of all stage boundaries—as contours—across the map area.

Exactly the same procedure was followed to track the westward retreat of the Top Edwards (tKed) boundary throughout the project area. Both mapping surfaces (tKed and bKed) for each stage were then drawn on one of 6 maps showing the outcrop of the Edwards Limestone (base as well as top) during stages 1 to 6.

Mapping the Retreat of the Edwards Plateau since Balcones Faulting

The present outcrop of the Edwards Limestone delineates the geomorphic feature we know today as the Edwards Plateau, and its distribution over the past represents the Plateau's westward and northward retreat following Balcones faulting. This retreat is depicted as 6 successive 3.5 Myr stages (Figs. 17B–17G), shown as "stop-action" images (Figure 17A shows the region at 21 Ma, immediately following first Balcones faulting and associated uplift). The base of the Edwards Limestone (bKed) is represented by a black line, stippled below the base. The top of the Edwards (tKed) is a black line delineating the base of the overlying Del Rio and/or Buda formations, shown on Figure 17G as thin (<40 ft) remnant outliers at the weathered top of the Edwards Plateau. Outcropping Edwards Group strata are represented by a light gray band. The advantage of showing this evolution as separate stages is that other aspects of landscape evolution, such as lateral migration of rivers and extension of tributaries, can be integrated with the incremental position of the erosional margin of the Plateau.

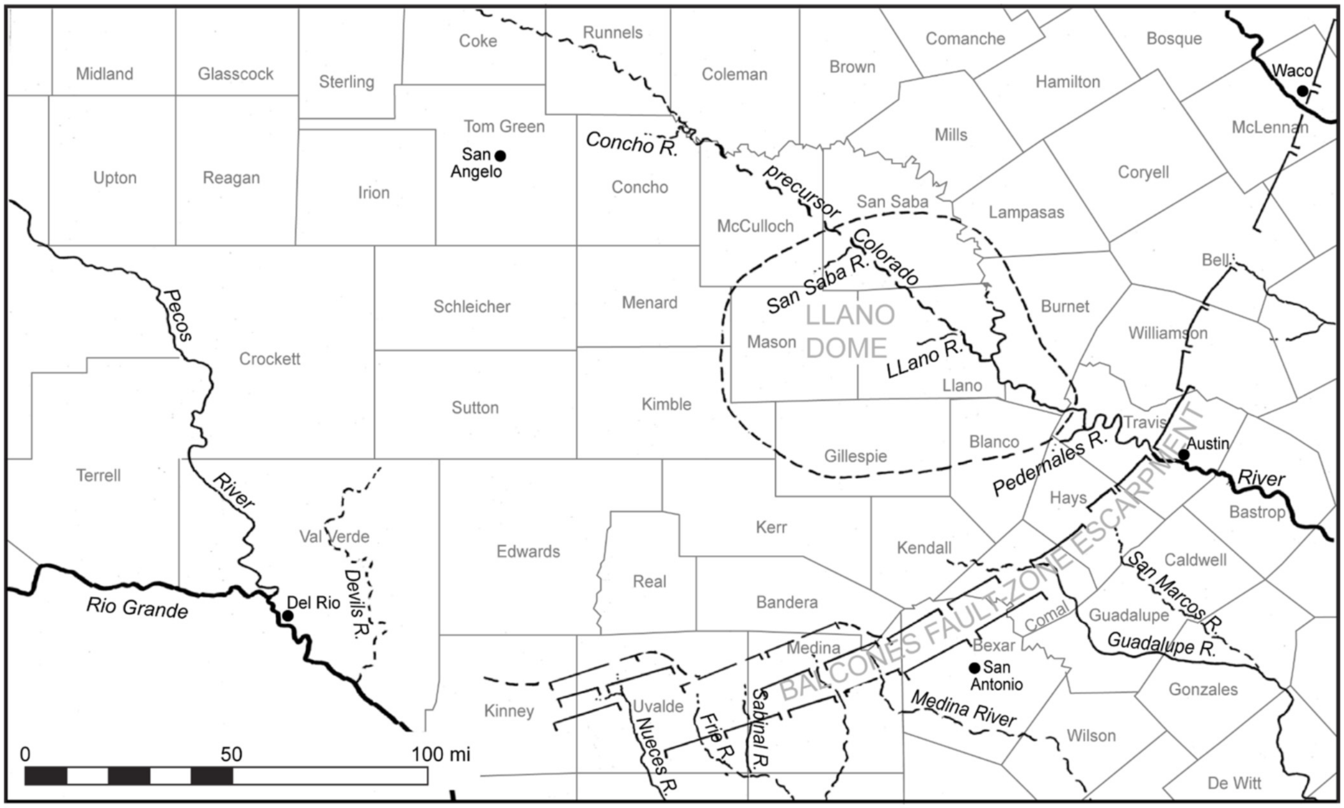
REVIEW OF STAGES 1–6 (21 MA TO PRESENT)

Stage 1 (21–17.5 Ma)

This review of the incremental stages of erosional slope retreat of the top (tKed) and base (bKed) of the Edwards Limestone begins 21 Ma, in the early Miocene. Figure 17A shows the region at the beginning of stage 1, immediately after the first major Balcones faulting, when the exposed top of the Edwards Limestone (or the thin Del Rio/Buda/Eagle Ford veneer) extended unbroken, westward beyond the Pecos River and northward beyond the Callahan Divide and Mescalero Escarpment. It is probable that a pre-faulting, slightly entrenched, low gradient drainage system, inherited from middle Paleocene through Oligocene time, already existed in the newly uplifted area. Its primary streams were the ancestral Rio Grande, Pecos, Colorado, and Brazos rivers (Galloway et al., 2011). It is possible that smaller precursor streams also existed, such as the Concho, San Saba, and Llano rivers (tributaries of the Colorado) and the Guadalupe, Medina, Nueces, and Devils rivers. Pre-existing entrenchment of meanders of precursor streams flowing across the southern and eastern peripheries of the recently elevated Edwards Plateau began to accelerate immediately upon uplift tied to Balcones faulting.

The ancestral pre-Balcones Colorado River flowed consistently southeastward from what is now the High Plains, across the buried Llano Dome, toward the Gulf shoreline, located at that time about 50 mi coastward from the newly emergent, linear scarp of the BFZ (Galloway et al., 2011; Rose 2016). The course

(17A) Start of Stage 1, 21 mya



(17B) End of Stage 1, 17.5 mya

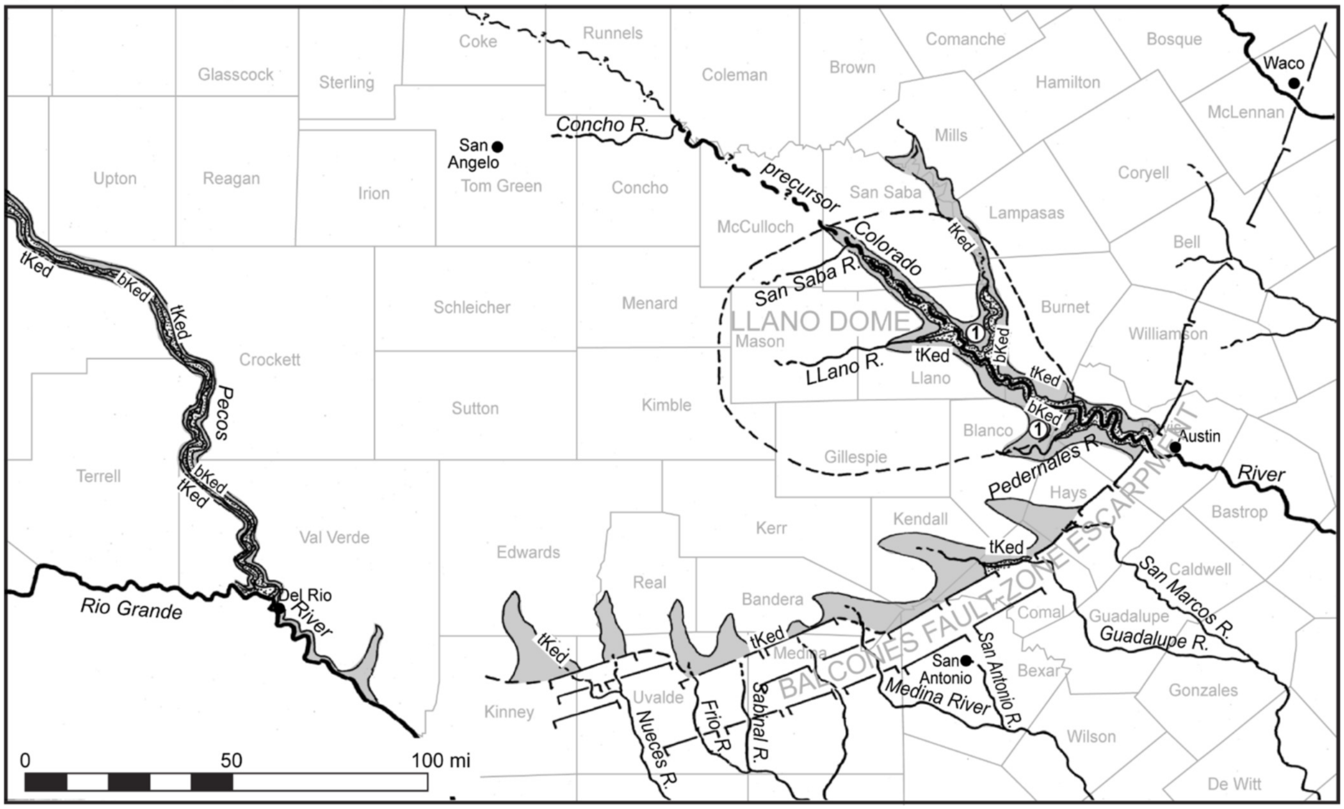
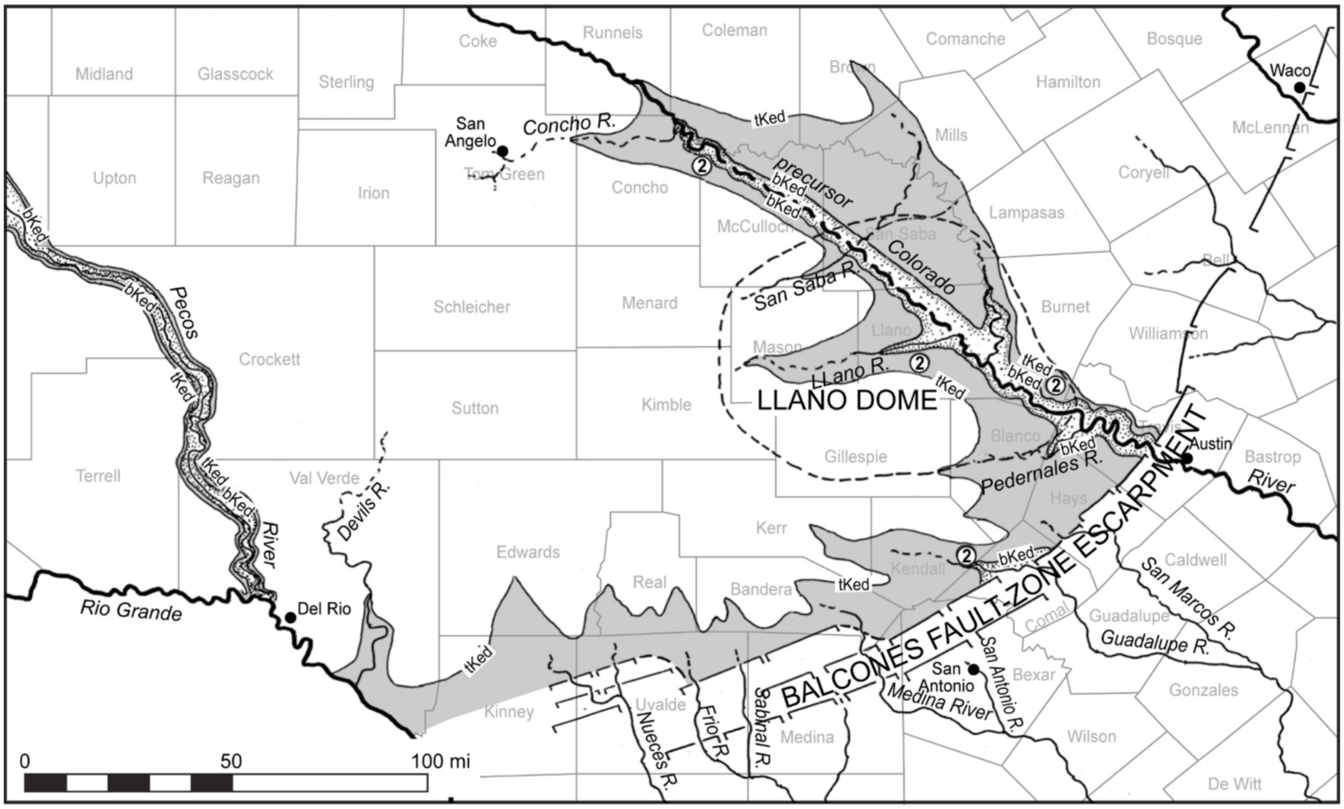


Figure 17. Evolution of Central Texas landscape after Balcones faulting and uplift of Edwards Plateau (datum = outcrop of Edwards Limestone): (A) start of stage 1, 21 Ma; (B) end of stage 1, 17.5 Ma; (C) end of stage 2, 14 Ma; (D) end of stage 3, 10.5 Ma; (E) end of stage 4, 7 Ma; (F) end of stage 5, 3.5 Ma; and (G) end of stage 6, present time.

(17C) End of Stage 2, 14 mya



(17D) End of Stage 3, 10.5 mya

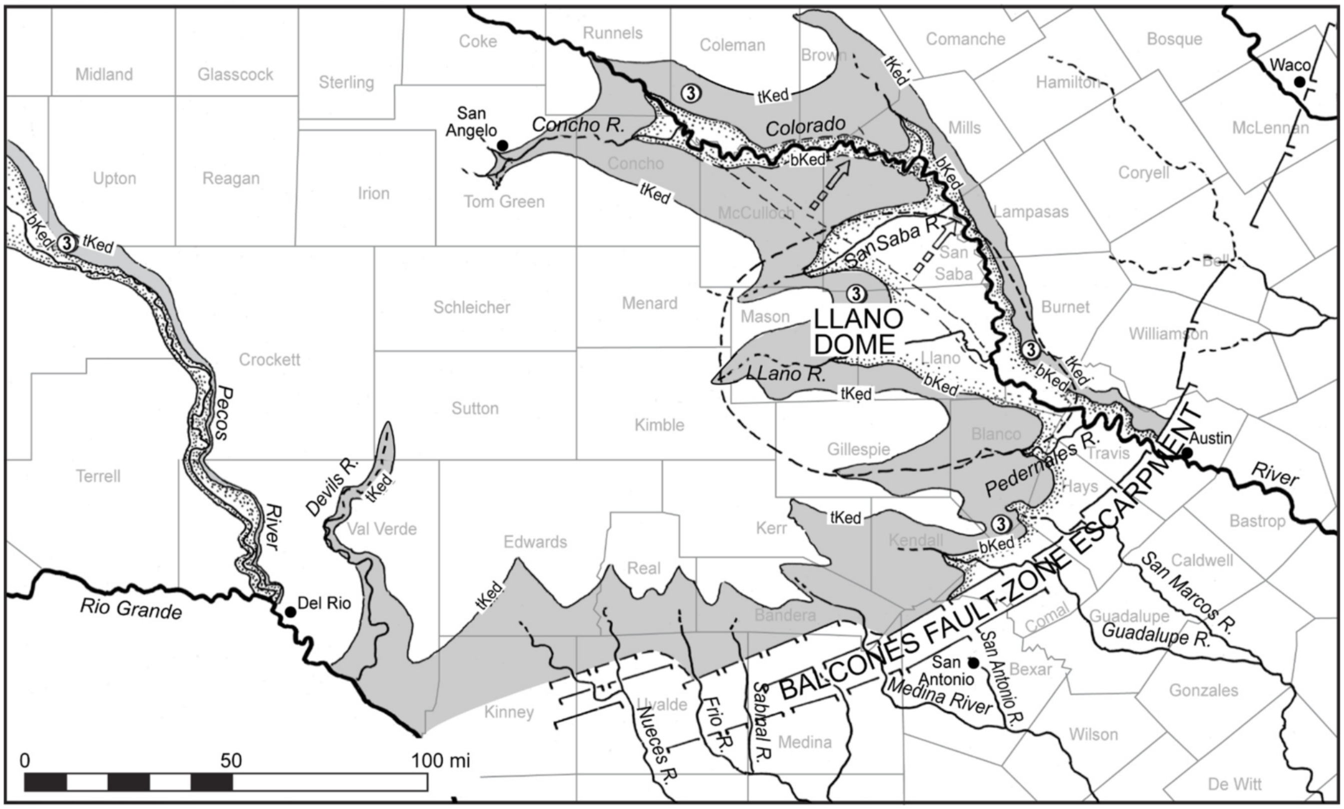
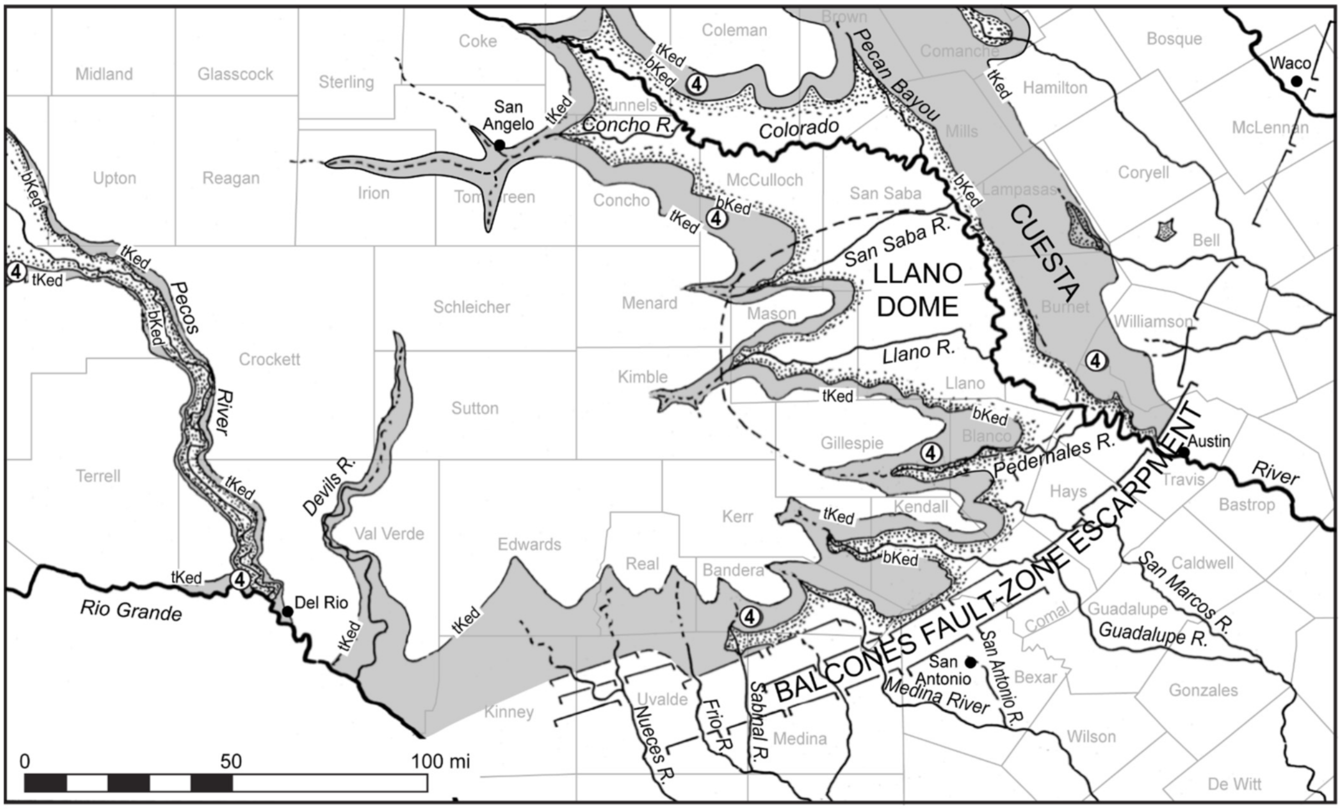


Figure 17, continued. Evolution of Central Texas landscape after Balcones faulting and uplift of Edwards Plateau (datum = outcrop of Edwards Limestone): (A) start of stage 1, 21 Ma; (B) end of stage 1, 17.5 Ma; (C) end of stage 2, 14 Ma; (D) end of stage 3, 10.5 Ma; (E) end of stage 4, 7 Ma; (F) end of stage 5, 3.5 Ma; and (G) end of stage 6, present time.

(17E) End of Stage 4, 7 mya



(17F) End of Stage 5, 3.5 mya

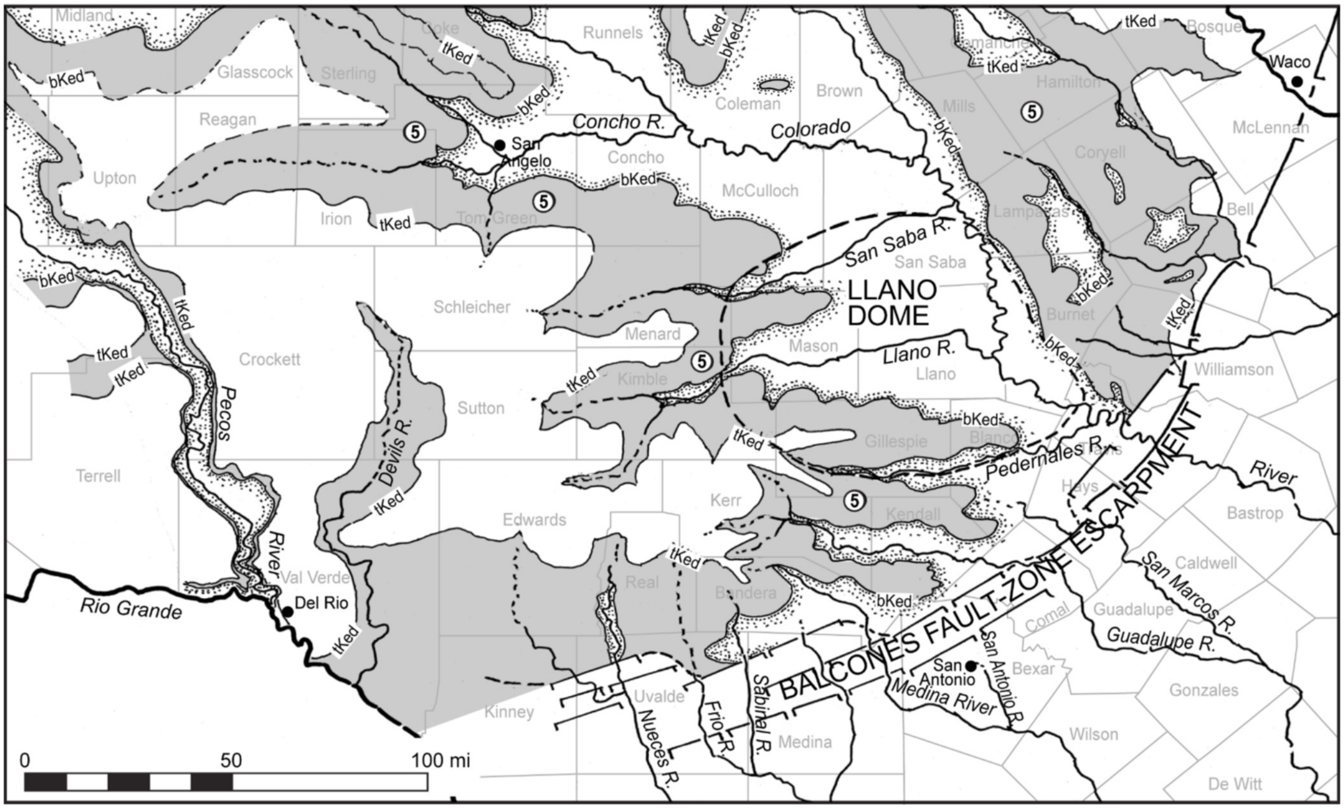


Figure 17, continued. Evolution of Central Texas landscape after Balcones faulting and uplift of Edwards Plateau (datum = outcrop of Edwards Limestone): (A) start of stage 1, 21 Ma; (B) end of stage 1, 17.5 Ma; (C) end of stage 2, 14 Ma; (D) end of stage 3, 10.5 Ma; (E) end of stage 4, 7 Ma; (F) end of stage 5, 3.5 Ma; and (G) end of stage 6, present time.

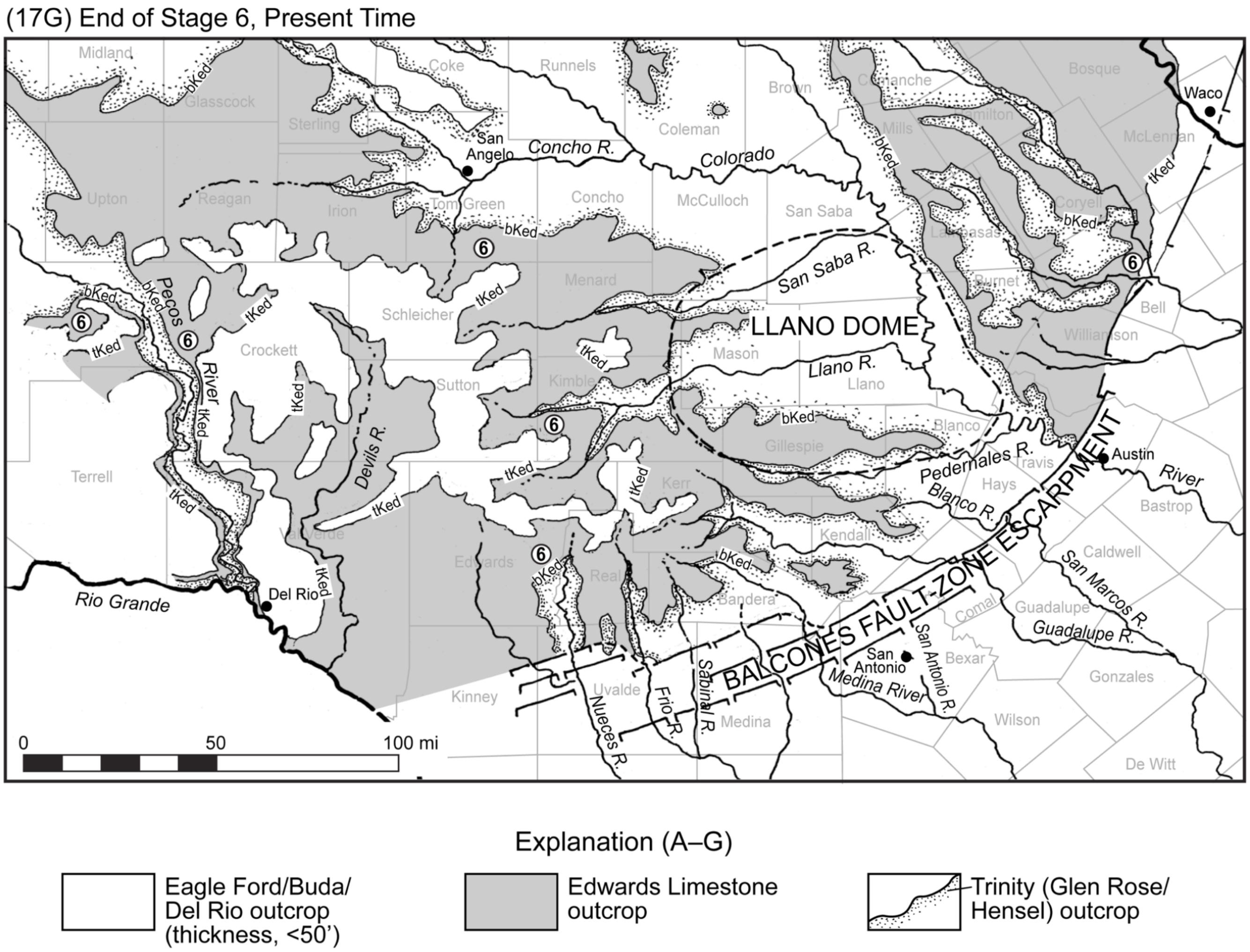


Figure 17, continued. Evolution of Central Texas landscape after Balcones faulting and uplift of Edwards Plateau (datum = outcrop of Edwards Limestone): (A) start of stage 1, 21 Ma; (B) end of stage 1, 17.5 Ma; (C) end of stage 2, 14 Ma; (D) end of stage 3, 10.5 Ma; (E) end of stage 4, 7 Ma; (F) end of stage 5, 3.5 Ma; and (G) end of stage 6, present time.

of the Brazos River was roughly 100 mi farther northeast, subparallel to the Colorado. The influence of Balcones faulting on the Brazos River was minimal.

Far to the west, the ancestral Pecos River already ran southeastward from recently elevated highlands, remaining consistently eastward of the Laramide doming in the Marathon area (King, 1937). Flowing southward through a broad precursor valley, the Pecos encountered harder carbonate rocks of the Edwards Group in far western Crockett County, Texas. In response, the Pecos valley, already entrenched, grew narrower southward, passing into a steep-walled gorge then more than 100 ft deep, on its way to join the Rio Grande, deepening its inherited meanders along the lower 50 mi of the river's course.

The Rio Grande had already begun its entrenchment during the Laramide Orogeny (late Cretaceous and early Tertiary), which continued during Neogene uplift of the Colorado Plateau (Galloway et al., 2011).

Like the Pecos River, the Colorado River had probably already begun to cut down into the Edwards Limestone before the onset of Balcones faulting. Independent evidence points to its pre-Miocene existence, such as its large-amplitude, deeply incised meanders, and sedimentary evidence in Oligocene sediments of the Texas Gulf Coast (Galloway et al., 2011). As previously noted, the depth of such incision is unknown, but our understanding of Oligocene paleotopography would make it unlikely to exceed perhaps 100 ft. In any case, by the end of stage 1, 3.5 Myr after regional uplift related to Balcones faulting (Fig. 15B), the Colorado River had probably carved a narrow winding gorge northwestward about 50 mi upstream of the Mount Bonnell Fault, the master fault in the Austin sector of the BFZ. This gorge was several hundred feet deep; it followed incised meanders probably inherited from a middle Paleocene progenitor stream. Farther northwest, the Colorado River flowed across resistant beds of Edwards Limestone that sloped gently to the northeast. The location of most of the Colorado's early tributaries is unknown, but three short tributaries have been identified: in northern Burnet County a south-trending tributary (precursor of Pecan Bayou) joined the ancestral Colorado from the east; a counterpart tributary (the Llano River precursor) joined from the west; in western Travis County, another east-flowing tributary (the Pedernales River precursor) joined from the west. It seems likely that the precursors of the San Saba and Concho rivers also existed, although little evidence for their location is apparent.

In western Comal County, the ancestral Guadalupe River cut further downward into previously entrenched meanders, carving a short, east-trending, v–shaped canyon through the Edwards Limestone, a few miles upstream from the main fault in that sector of the BFZ. Similar canyons serrated the south-facing scarp of the recently elevated Edwards Plateau, the precursor valleys of the Blanco, Medina, Sabinal, Frio, and Nueces rivers. These surface streams flowed eastward across down-faulted terranes of Edwards Limestone and began to recharge them.

Otherwise, the landscape west and north of the BFZ was an elevated expanse of resistant limestone strata, thinly veneered with spare soils, at or near the top of the Edwards Limestone (tKed), or just above, in the thin Buda/Del Rio sequence.

Stage 2 (17.5–14 Ma)

During stage 2, the Colorado River deepened, widened, and extended its gorge upstream from the Mount Bonnell Fault, further enlarging its entrenched meanders (Fig. 17C). Farther upstream, the Colorado canyon extended itself northwestward, into (and across?) San Saba County. Western tributaries such as the Pedernales, Llano, and San Saba rivers cut deeper into the Edwards Limestone near their respective mouths, connecting with the valley of the Colorado River. An inferred eastern tributary (the precursor of Pecan Bayou), cut a narrow valley into the Hensel Sandstone; this valley terminated northward in two forks (Fig. 17B).

To the south, just west of the BFZ, the Guadalupe River widened and deepened its winding canyon, extending it to 15 mi west of the master fault. Short upper tributaries of the Guadalupe rose abruptly from the steep slopes of the Edwards Limestone along the eastern margins of the Plateau. The ridge-and-valley terrain along the southern margin of the Plateau grew wider and more deeply dissected by headward erosion of south-flowing streams, which then crossed down-faulted blocks of Edwards Limestone, recharging them.

Throughout stage 2, the ancestral Pecos River continued to cut downward through its narrow gorge across the rising limestone terranes of the Edwards and Stockton plateaus. Incised meanders continued to be further entrenched in the lower 50 mi of its course above the Rio Grande.

Stage 3 (14–10.5 Ma)

During stage 3, the deepening valley of the Colorado River extended itself farther upstream, and into the eastern drainages of the Pedernales, Llano, San Saba, and Concho river tributaries (Fig. 17D). On the southeast flank of the Llano Dome, the Colorado River and its western tributary, the Llano River, cut down through lower Edwards Limestone, Glen Rose marl and Hensel Sandstone, into Precambrian crystalline rocks.[5] On the dome's northeast flank, the Colorado cut down into hard, northeast-dipping Paleozoic strata, and the river began to shift its course laterally to the northeast, forming the Great Bend of the Colorado in response to those structural influences (Fig. 14), possibly in combination with eastward diversion of the Colorado River through stream piracy of the Colorado by the inferred west-reaching tributary of Pecan Bayou (Fig. 17C).

The dissected area east of the Edwards Plateau grew wider as the Colorado River shifted toward the Great Bend. Its western tributaries extended themselves eastward, keeping up with the eastward shift of the river, even as their heads continued their relentless westward erosion. The Colorado's eastern tributaries were gradually consumed as the parent stream migrated eastward. This generated the marked asymmetry of the tributaries of the Colorado River drainage basin between Pecan Bayou and the BFZ (Fig. 13).

During stage 3, a narrow, ragged, sloping landscape developed in the Blanco and Guadalupe river valleys, between the inboard-most Balcones faults and the high, east-reaching interfluvial divides of Edwards Limestone bounding the rivers. This was the precursor of the Hill Country province, and its area would expand as the digitate eastern erosional scarp of the Edwards Plateau continued its westward retreat. Spring-flows of the Blanco and Guadalupe rivers issued from the base of the Edwards Plateau aquifer, ran across older Cretaceous formations (mostly Glen Rose limestone and marl), and crossed into downfaulted blocks of Edwards Limestone, recharging the ancestral Edwards (BFZ) artesian aquifer.

The southern margin of the Edwards Plateau became increasingly digitate as the north-reaching valleys of the precursor Medina, Sabinal, Frio, Nueces, and Devils rivers grew longer and wider, but continued to flow within the Edwards Group outcrop. Farther west, the Pecos River eroded ever-downward as the western Edwards Plateau continued its gentle uplift.

Stage 4 (10.5–7 Ma)

By the start of stage 4 the Colorado River had completed its northeastward shift, assuming the present course of the Great Bend (Figs. 17E, 13, and 14). The Colorado appropriated the further southward course of Pecan Bayou connected farther downstream with the head of the short south-flowing tributary of the Colorado in northern Burnet County. This is the present course of the Colorado River, a curvilinear path adjacent to the face of the long cuesta formed by the east-dipping Lower Cretaceous Trinity and Fredericksburg succession (Travis Peak, Glen Rose, Paluxy, Walnut, Comanche Peak, and Edwards). This cuesta extends unbroken southward, with the Colorado River flowing closely alongside, to the Mount Bonnell Fault just west of Austin.

The lowland on the west side of the Colorado River (created in the wake of the river's shift northeastward) continued to broaden, extending during stage 4 from the mouth of the Concho River southeastward through the lower reaches of the San Saba and Llano river valleys, which had extended their courses eastward to match the Colorado's eastward migration. By the end of stage 4, the east-facing erosional frontal scarp of the Edwards Plateau now snaked southeastward along the western side of the Colorado River's broad valley, through Concho, central McCulloch, eastern Mason, and southern Llano counties. Once the Colorado River had rejoined its original course downstream from the mouth of the Llano River, the western side of its valley grew narrower, conforming to its original symmetry in the 50 mi downstream to the Mount Bonnell Fault at Austin.

During stage 4, the San Saba and Pedernales rivers cut downward into lower Paleozoic sedimentary formations, whereas the Llano and Colorado rivers, located over the center of the Llano Dome, both cut more deeply into its Precambrian core, as shown by the presence of these characteristic rock types among ancestral Colorado River gravels far downstream in the Goliad Formation.

From the Blanco River southwest, the aforementioned serrated, sloping landscape that emerged during stage 3, continued to extend southwestwardly to include the Medina and Frio river valleys, and to further widen, from the inboard-most Balcones faults to the high, westwardly-retreating interfluvial divides of Edwards Limestone separating the Blanco, Guadalupe, Medina, Frio, and Nueces rivers. Headwaters spring-flow from these rivers continued to recharge downthrown fault blocks of Edwards Limestone in the BFZ.

East of the Colorado River valley, in the Lampasas Cut Plain province, newly established river drainages and local structure

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[5] Maxwell (1970) reported the presence of pebbles of Precambrian crystalline rocks derived from Llano Uplift terranes in gravels of the Goliad Formation (upper Miocene to Pliocene [15–5 Ma], but did not specify whether they were found in the lower Goliad (late Miocene) or upper Goliad (Pliocene) part of the succession.

combined to expose the base of the Edwards Group in eastern Lampasas and western Bell counties. Otherwise, the Edwards Group, representing the eastern counterpart of the Edwards Plateau, was exposed across a wide NNW–SSE band from Comanche to Williamson counties.

On the west side of the Edwards Plateau, entrenchment of the Pecos River persisted as regional uplift of the Colorado Plateau continued.

Stage 5 (7–3. 5 Ma)

The future configuration of the eastern and southern margins of the Edwards Plateau was already established by the beginning of stage 5: a serrate, erosional scarp facing east and south, skirting the valleys of all streams draining the Edwards Limestone highlands to the west and northwest. That scarp was formed by the resistant Edwards Limestone, rising steeply above gentle slopes developed on the soft, underlying, Trinity-age sandstones, mudstones, and marls, much as it does today, but 10 to 30 mi farther eastward (downstream). East of the Colorado River, erosion caused the top of the Edwards to retreat eastward across the Lampasas Cut Plain (Fig. 17F).

On the Colorado River, the base of the Edwards Limestone lay a few miles west of Ballinger. On the Concho, it lay at San Angelo, where the North, Middle, and South Forks converge. The valley of upper Pecan Bayou, floored now by soft Trinity-age Travis Peak sandstone, grew wide. San Saba River crossed the base of the Edwards along the Mason–McCulloch county line, and the Llano River crossed it along the Mason-Kimble county line. The Pedernales River crossed it in eastern Gillespie County, near Stonewall, and the Blanco River crossed it a few miles west of Blanco town. The Guadalupe River crossed into upper Glen Rose strata a few miles downstream from Kerrville, as did the Medina River, between the towns of Bandera and Medina. Down-cutting by the Frio and East Nueces rivers during stage 5 exposed the base of the Edwards Limestone. Farther west, the West Nueces and Devils rivers still flowed entirely within the south-dipping Edwards Limestone throughout their southward courses.

The Colorado River ran in upper Paleozoic formations southward from Ballinger, lower Paleozoic rocks downstream from the mouth of the San Saba River, and in Precambrian crystalline rocks from present Buchanan Dam south nearly to Marble Falls, as shown by Maxwell's (1970) discovery of pebbles of Precambrian crystalline rocks from the Llano Uplift in Pliocene Colorado River gravels. The Concho River ran in upper Paleozoic strata starting a few miles east of San Angelo, and the San Saba flowed through lower Paleozoic beds for the last 40 mi before its junction with the Colorado. Running eastward across the Llano Dome, the Llano River flowed over lower Paleozoic strata in the western half of Mason County, and through Precambrian gneiss, schist and granite for the next 70 mi, to its juncture with the Colorado River. The Pedernales River continued to run across faulted, mostly lower Paleozoic rocks in western Blanco County, before encountering east-dipping Lower Cretaceous strata upstream of its junction with the Colorado River. East of the Blanco-Kendall county line, the Blanco River ran in the Glen Rose Formation until crossing the BFZ. The Guadalupe River first encountered Glen Rose strata between Kerrville and Comfort, and the Medina River ran in the Glen Rose outcrop, starting about 5 mi west of Bandera town.

In the Lampasas Cut Plain province east of the Colorado River, tributary streams of the Little River drainage system (Lampasas, Cowhouse, and Leon) cut downward into Trinity-age strata.

The Pecos River continued its downcutting throughout stage 5; the Pecos gorge effectively separated the Stockton Plateau from its more extensive eastern counterpart, the Edwards Plateau. The Pecos Canyon became wider at the mouth of its eastern tributary, Howard's Draw. Downstream, entrenched meanders in the lower 25 mi of the river grew deeper and more spectacular.

Stage 6 (3.5 Ma to present)

The history of the eastern Edwards Plateau during the later Pliocene, Pleistocene, and Holocene is relatively simple—the basic landscape configuration was maintained, modified only by steady erosional retreat of the ragged frontal scarp along the valleys of the upper Colorado, Concho, San Saba, Llano, Pedernales, Blanco, Guadalupe, and Medina rivers. Retreat of the base Edwards outcrop in river valleys ranged from 10 to 20 mi, whereas retreats of slopes along the sides and eastern ends of interfluvial divides ranged from 3 to 5 mi. By the end of stage 6, the landscape of the Edwards Plateau region was what we see today (Fig. 17G).

Continued erosion of south-dipping Edwards limestone strata in the valleys of the Frio, East Nueces, and West Nueces rivers exposed and enlarged the outcrop areas of the underlying Glen Rose Formation, but the south-flowing Devils River did not erode deeply enough to expose pre-Edwards strata.

The Hill Country province, located between the BFZ and the west-retreating slopes of the Edwards Limestone, continued to expand. East-flowing spring-flows from the Blanco, Guadalupe, Medina, and Sabinal rivers continued to charge downthrown blocks of Edwards Limestone in the BFZ, enlarging the Edwards artesian aquifer.

Immediately west of the cuesta along its east bank, the Colorado River continued to cut downward, now well into the Glen Rose Formation. The remnant Jollyville Plateau, once connected westward to the Edwards Plateau, still survived, perched above the entrenched Colorado, on the northwest edge of Austin.

The valleys of the Lampasas Cut Plain province deepened, enlarging the pre-Edwards outcrop areas of the Little River drainage basin.

The valley of the upper Pecos River widened north of the Pecos gorge, encroaching eastward on the Edwards outcrop and further defining the southwest face of the Mescalero Escarpment. Farther south, the Pecos gorge continued its long entrenchment, joining the Rio Grande at grade, elevation about 1100 ft above sea level.

EVOLUTION OF THE EDWARDS AQUIFERS

The foregoing original research and conclusions make it possible to generate a synthesis of geologic, geomorphic, and hydrologic scenarios within which may be integrated the present published understanding of both Edwards aquifers: (1) the unconfined Plateau Aquifer (the source of all streams that cross outcropping Edwards carbonate strata in the BFZ), and (2) the Edwards (BFZ) aquifer, with its three component zones: (a) recharge zone, (b) artesian zone; and (c) saline water zone. The formulation of such a scenario is also informed by evidence from selected regional karst features. Much of this section of the report is based on published work of others, as cited.

Significance of Karst Features on Edwards Plateau Geohydrologic History

Like many limestone terranes, the Edwards Plateau is today literally honeycombed with caves. Locals are familiar with "whistling wells"—water wells that intercept caves between the surface and the water-bearing strata several hundred feet below, resulting in audible outflow of air from the casing during the passage of cold fronts, equalizing barometric pressure between the prevailing atmosphere and caves below. Travelers along Interstate 10 between Kerrville and the Pecos River cannot fail to notice, in roadcuts along the route, many prominent vertical "pipes" in Edwards strata, filled with unconsolidated calcareous mudstone, with signs of collapse near their tops.

Wermund et al. (1978) described and analyzed fracture systems in the southern Edwards Plateau. They showed that caves are controlled by long- and short-fracture systems, with long-fractures probably being the more significant. They identified two groups of caves in their southern Plateau study area—those in the deeply dissected southern and eastern sectors that were controlled by Balcones-related fractures, and those in the relatively undissected western and northern sectors that were controlled by basement-related fractures. These facts led them to speculate that two separate ages of cave formation may have occurred. Wermund et al. (1978) also identified two types of Edwards Plateau caves, oblate and linear, the latter being clearly fracture controlled.

Kastning (1983) described two main classes of caves on the Edwards Plateau: deep vertical caves ("sinkholes") and long horizontal caves, many having several different levels. These two types appear to correspond to the oblate and linear categories of Wermund et al. (1978). Kastning (1983) related these differences to variations in stream incision, fracturing, stratigraphic variations, and lithology. He assigned the later stages of cavern development to the Pleistocene and Quaternary but did not indicate when such processes began. The writer suggests that such cavern development may have originated in the Miocene.

Sinkholes

In the Langtry area (Val Verde County), Kastning (1983) described 4 deep sinkholes in the Devils River Limestone (shelf-margin facies laterally equivalent to the Fort Lancaster and Segovia formations). He related their occurrence to vertical fracturing and their depth (250 to 370 ft) to rapid incision of the Rio Grande and its tributaries and consequential steepened hydraulic gradients. Kastning (1983) believed cave development began in early Pleistocene, with deep cavern development related to rapid Pleistocene incision of the Rio Grande and associated tributaries and lowered base levels. This work suggests that such events probably extend back into the Miocene.

Another deep vertical cavern is the Devil's Sinkhole in northern Edwards County, about 7 mi northeast of Rocksprings. It is about 350 ft deep, with a chimney about 100 ft in diameter above a collapse-enlarged lower room nearly 500 ft across and 200 ft high, with a large central talus cone centered under the chimney. It is developed in the upper Segovia Formation, but reaches downward into the upper Fort Terrett Formation. There is no surface depression around the periphery of the sinkhole. The Devil's Sinkhole is unique in that the lower parts of the cave, peripheral to the outer edges of the talus cone, penetrate the free water table.

Horizontal Caves

Kastning (1983) described three horizontally extensive caves in the area of Sonora, Sutton County, Texas: (1) Caverns of Sonora (1.37 mi long); (2) Felton Cave (1.27 mi long); and (3) Silky Cave (0.25 mi long). All three caves developed in the upper Segovia Formation, more than 100 mi from the nearest Balcones faults. Most passages in such caves are conformable with susceptible stratigraphic horizons within the upper Segovia, and passages are controlled by fractures that have been enlarged through solution.

These caves feature multiple levels of horizontal cavern development, related to abrupt drops in base level, as Neogene and Quaternary incision and headward erosion of the Edwards Plateau proceeded. Each lower level successively represents a more recent stage of active cave development; thus such caverns represent relict zones that reflect the history of terrain downcutting and drops in paleo water-tables. Today they lie well above valley floors high on the Edwards Plateau, "yet they represent moderately well-integrated flow systems that evolved early in the erosion and dissection of the [P]lateau" (Kastning, 1983, p. 109). As with his discussion of sinkholes, Kastning (1986) assigned the later stages of such cavern development to the Pleistocene and Quaternary, but the reconstructions suggest such caverns may reflect Miocene events.

Kastning (1986) also carried out research on caves in the recharge zone of the BFZ, especially Natural Bridge Caverns, Bracken Bat Cave, and Double Decker Cave, west of New Braunfels in Comal County, Texas. Here horizontal caverns developed mostly in highly fractured upper Glen Rose limestone, reaching up into the lower Edwards ("Walnut Formation" or lower Kainer Formation). Kastning (1986) assigned a Pleistocene age to the latter stages of the evolution of such caves. He implies, however, that the earlier stages of cavern development may have started in the late Miocene, after Balcones faulting (Kastning, 1986, p. 99).

Epigenic vs. Hypogenic Karst Processes

Until recently, all karst processes were thought to be epigenic, that is, related to surface waters moving downward through mostly carbonate or gypsiferous soluble rock succession. Klimchouk (2007) demonstrated that hypogenic processes, related to mineralized subsurface waters moving upward, were also important in the subsurface generation of vugs and caves. Veni (2018) described examples of hypogene karst in the Edwards Plateau, especially in the lower levels of the Caverns of Sonora (related to upward leakage of hydrocarbons from the underlying Sonora gas field), and in deep caves of the Carta Valley Fault Zone in western Edwards and northeastern Val Verde counties). Schindel and Gary (2018) reviewed evidence of hypogenic karst in the Edwards (BFZ) artesian and saline water zones.

Although hypogenic processes were probably responsible for some early karst formation in the Edwards Plateau, as well as the BFZ, a balanced evaluation suggests that most existing karst in the region is epigenic, in many cases enlarging and obliterating earlier hypogenic karst. However, hypogenic processes may have been important agents in creating karstic aquifers in the artesian zone of the Edwards (BFZ) aquifer, through the mixing of fresh and mineralized subsurface waters, as discussed subsequently.

Karstic Plains and Relict Soils

Karstic plains are relict landscapes. Woodruff and Abbott (1979, 1986) identified karstic plains in the BFZ on divides between San Antonio River, Cibolo Creek, Guadalupe River, Blanco River, Onion Creek, and Barton Creek and observed—significantly—that they occur adjacent to sites where stream piracy has taken place. Cooke et al. (2007) documented the locations of red relict soils rich in clay and silica developed on top of Edwards Group carbonate rocks and proposed that such soils were produced through in-place weathering of the Del Rio Clay as well as weathering and partial solution of the underlying Edwards Limestone. Interestingly, their map of red soil localities on the Edwards Plateau is consistent with the distribution and thickness of the Del Rio Formation on the Edwards Plateau (Rose, 2016). The most prominent area of relict red soils on the Edwards Plateau coincides with the crest of the Medina Arch, suggesting they may be related to deep weathering and solution.

Edwards Plateau Aquifer

Three essential geologic properties combine to form the unconfined Edwards Plateau Aquifer of the present day:

(1) a relatively impermeable zone near the base of the Edwards Limestone;

(2) porous and permeable strata above the impermeable zone; and

(3) a thick succession of permeable rock exposed to meteoric water over a wide area.

Today, the Plateau aquifer ranges up to about 250 ft thick above the base of the Edwards. The horizontal caves in Sutton County described by Kastning (1983) are all above the present water table, indicating that past water tables were higher than they are now.

Although caves and enlarged fractures are present throughout the Edwards Limestone of the Edwards Plateau, matrix porosity and permeability generally increase downward, being concentrated in the Fort Terrett Formation (Rose, 1972). Zones of greatest transmissivity are all secondarily altered by solution of original depositional textures. Most common types of transmissive rocks are:

(a) thick and widespread intervals of burrowed biomicrite of the Basal Nodular and Burrowed members of the Fort Terrett Formation in which the burrow-fillings are more porous than the matrix, producing a honeycomb-like texture;
(b) intervals of rudistid-rich biomicrite in which the whole shells of rudist fossils have been dissolved, again generating a honeycomb-like texture;
(c) widely extensive intervals of evaporite collapse breccia of the Kirschberg Member, which have been intensely solutioned in the present geomorphic cycle, leading to enhanced collapse and development of network porosity zones;
(d) dolomitization of biomicrite beds, which are typically more porous and permeable than limestones; and
(e) limestone and dolomite rocks adjacent to fractured zones do not show strong association with particular stratigraphic zones or beds. Most caverns and sinkholes show strong affinities for areas of intense fracturing and long lateral extent (Wermund et al., 1978)

Secondary enhancement of porosity and permeability took place from Miocene to the present (Loucks et al., 2018), when wide areas of Edwards outcrop were exposed to subaerial weathering and erosion. The unconfined Plateau aquifer was established at this time, and headwater streams formed the base flow for rivers and their tributaries issuing radially from the deeply dissected periphery of the Plateau.

It seems likely that the upper surface area of the Plateau aquifer was greatest during stages 1 and 2, about 21–14 Ma, after regional uplift associated with Balcones faulting, and erosion along the BFZ had exposed the basal Edwards so as to promote outward flow of ground water issuing from springs in the lower part of the Edwards Limestone, especially the Fort Terrett and Kainer formations. This was also the time of greatest stream piracy in the BFZ, which accentuated the outflow of groundwater from Edwards springs (Woodruff and Abbott, 1986). As the area of exposed Edwards outcrop gradually shrank westward through headward erosion, the volumetric recharge of the Plateau aquifer must also have begun to decrease. The upper surface of the aquifer gradually declined thereafter, as base level of area streams declined through the Miocene, Pliocene, and Holocene, as described by Kastning (1983).

Edwards Porosity and Permeability Patterns in the BFZ

The Edwards (BFZ) aquifer can be usefully separated into three geologic subzones, from updip to downdip (Fig. 18):

(1) recharge zone, where down-faulted Edwards Group strata in fault blocks are recharged by area streams that cross the outcrop, and the Edwards Aquifer is unconfined;
(2) artesian zone, where faulted Edwards Group strata are in the shallow subsurface, confined by impermeable overlying layers, especially the Del Rio Clay; and
(3) saline zone (previously known as the "bad-water zone"), where Edwards rocks in the subsurface adjacent to and downdip from the Edwards artesian zone are saturated with mineralized, sulfide-rich subsurface waters having total dissolved solids ordinarily exceeding 1000 mg/l.

Edwards (BFZ) Recharge Zone

In general, matrix porosity and permeability patterns commonly found in Edwards Group carbonate rocks of the Edwards Plateau are also prominent in outcrops of the Edwards recharge zone. Abbott (1975) recognized the same main carbonate facies that are prominently susceptible to porosity and permeability development that Rose (1972) does:

(1) burrowed sparse biomicrite,
(2) caprinid biolithite,
(3) collapse breccia, and
(4) bedding partings.

Chief differences have to do with (a) much more common solution-enhanced fracturing and faulting in recharge-zone outcrops; (b) clear evidence of more extensive and pervasive karstification of carbonate rock fabrics by undersaturated surface waters; and (c) greater porosity and permeability development in the upper Edwards cycle (the Person Formation) than in the lower cycle (Kainer Formation). Particularly affected by solution is the Kirschberg collapse breccia (upper Kainer Formation), which is commonly represented only by a red-stained, deeply altered and weathered rubble zone reflecting extensive solution by transient subsurface water (Young, 1986). Terra rossa deposits also fill vertical solution-pipes and horizontal bedding fissures. Otherwise, primary rock fabrics and diagenetic products such as dolomite and dedolomite are present as they are in Edwards Plateau outcrops. In general, severe karst development is no more widespread in the recharge zone than in the artesian zone.

Karst-enlarged fractures and faults in the BFZ recharge zone created subterranean passageways by which streams originating from the Edwards Plateau aquifer might recharge downthrown fault blocks of Edwards Limestone across which they flow. These subsurface waters could then enter the Edwards (BFZ) artesian aquifer, which is confined between poorly transmissive strata of the underlying Glen Rose Formation below, and the impervious Del Rio Clay above.

Edwards (BFZ) Artesian Zone

Ellis (1986) reported that fresh water from the Edwards (BFZ) artesian zone was saturated only with respect to calcium carbonate; sulfides and sulphates were low, total dissolved solids were typically 250–350 mg/l, and chloride content was less than 25 mg/l. However, Senger and Kreitler (1984) and Woodruff and Abbott (1986) emphasized the severe and maintained dissolution of Edwards limestones by undersaturated waters in the BFZ. The clear and widespread occurrence of such extensive solution in BFZ outcrops would seem to verify the view of Senger and Kreitler (1984) and Woodruff and Abbott (1986). More recent work by Smith et al. (2017) verified the presence of mildly acidic water in the fresh water zone of the Barton Springs Segment of the Edwards Underground Aquifer.

Original Edwards Group carbonate rock fabrics in the Edwards (BFZ) artesian zone are similar to those in the Edwards Plateau and the Edwards (BFZ) recharge zone. The presence of widespread karsted carbonate terranes in the recharge zone is seen as analogous to the measured and mapped porous trends in the artesian zone (Maclay and Small, 1986; Hovorka et al., 1996). Late-stage conversion of dolomite to dedolomite by calcium-saturated water (Abbott, 1975; Ellis, 1986) rendered dolomite less abundant in the Edwards (BFZ) artesian aquifer than in the Plateau aquifer.

Woodruff and Abbott (1986) noted the greater karstification and cavernous porosity in the Medina/Cibolo/Guadalupe/San Marcos segment of the Edwards recharge zone and artesian

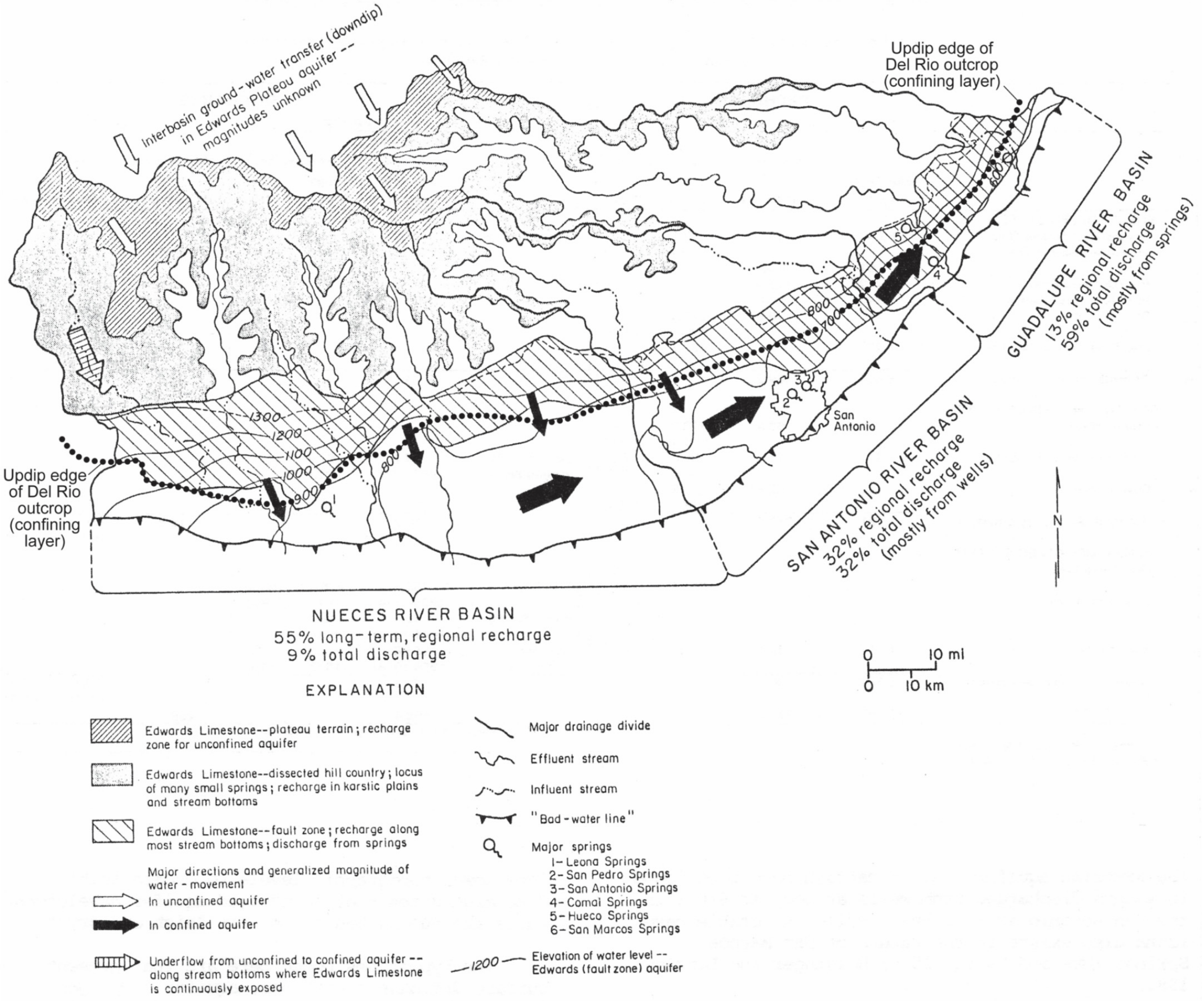

Figure 18. Edwards aquifer system (from Woodruff and Abbott, 1986).

zones, citing the enhancing effects of stream piracy as one of the main causes (Fig. 18). Following Abbott (1975), they also related higher early porosity and permeability in the Person Formation to the top-Person disconformity around the axis of the San Marcos Arch. Maclay and Small (1986) and Hovorka et al. (1996) presented figures showing that average porosity in the Edwards Group was highest in the central sector of the Edwards (BFZ) artesian zone, and that porosity in the Person Formation was greater than in the underlying Kainer Formation (Figs. 19A and 19B):

(1) that sector contains the greatest concentration of faults, as well as the greatest vertical displacement, in the BFZ, thus providing more fracturing to serve as conduits for entry of surface water into the Edwards (BFZ) artesian aquifer;
(2) that sector has the 5 largest springs in the BFZ, including San Marcos Springs, the lowest discharge point along the central sector of the Edwards (BFZ) artesian aquifer, providing for abundant through-put of dissolving surface waters;
(3) dissolution processes acted longer in the central sector than to the west so that sector was dissected earlier in the evolution of the BFZ than the western sector (Medina/Uvalde and Kinney counties);
(4) carbonate rock available for dissolution and diagenesis in the Person Formation, (more susceptible to solution than the underlying Kainer Formation according to Hovorka et al. (1996) diminishes northward from San Marcos due to stratigraphic thinning to zero just north of Austin (Rose, 1972, 2017).

Edwards (BFZ) Aquifer Basinward from the Saline Water Interface

In conventional fresh water aquifers, salinity and total dissolved solids (TDS) of contained waters tend to increase gradually basinward, eventually becoming unpotable and highly mineralized. The Edwards (BFZ) artesian aquifer is different. The highly porous and permeable, apparently cavernous in some cases, carbonate strata that transmits potable fresh water grades laterally to unoxidized dolomite and limestone saturated with brackish or saline formation waters, low matrix porosity with little evidence of solution-enlargement of pores or fractures by moving water

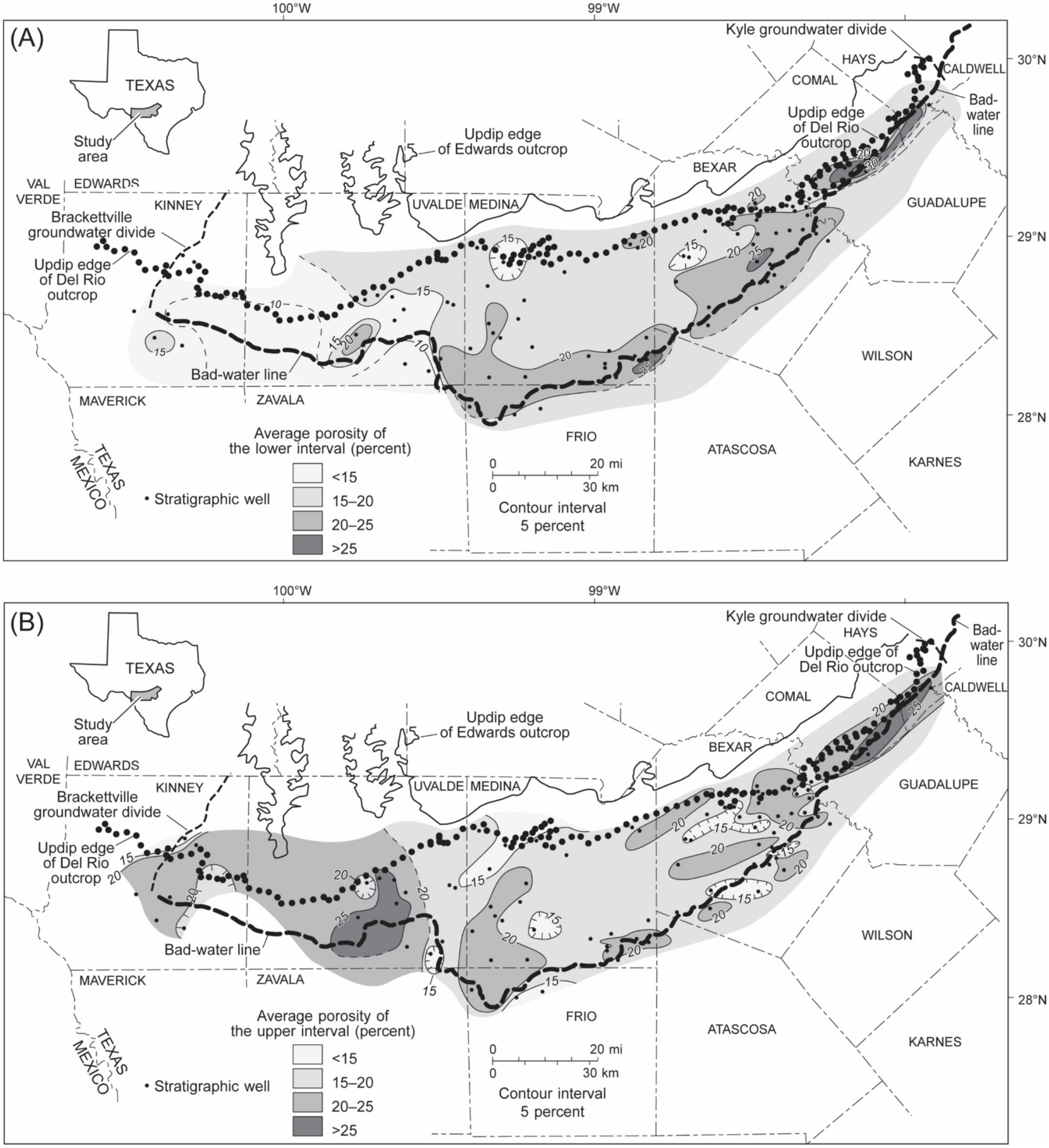

Figure 19. Average porosity in Edwards Aquifer (from Hovorka et al., 1996). (A) lower part of Edwards Aquifer (Kainer/lower Devils River/West Nueces/McKnight interval. (B) Person, upper Devils River/Salmon Peak interval.

(Abbott, 1975; Hunt et al., 2014). This transition zone is now referred to as the Edwards artesian-saline water interface (formerly called the "bad-water line"). In the central and northern sectors of the Edwards (BFZ), where the width of the artesian zone is narrow, this transition is commonly only a few hundred yards wide (Hunt et al., 2014), and apparently fault constrained. Where the artesian aquifer is wide, in southern Medina and western Bexar counties, this transition is as much as 10 mi wide, with marked interfingering of updip and downdip carbonate textures (Hovorka et al., 1996). Edwards rock fabrics downdip from the saline water interface are similar to those encountered throughout the subsurface of the San Marcos Platform, including deep Edwards fault-trap reservoirs at Fashing and Person oil and gas fields (Rose, 1972; Kozik and Richter, 1974).

The processes by which Edwards Group formation waters of differing origins combine downdip along the Edwards (BFZ) artesian/saline water interface are complex, but mixing of deep saline waters migrating updip, with fresh or brackish waters migrating downdip, seem to be related to creation of porosity, some karstic. Subsurface waters migrating along normal faults also seem to be involved (Land and Prezbindowski, 1981; Deike, 1990; Groschen and Buszka, 1997; Hoff and Dutton, 2017; Smith et al., 2017; Schindel and Gary, 2018).

The concept of hypogenic karst processes may explain the origin of complex and cavernous karst in the Edwards (BFZ) artesian aquifer. Passageways are created first by hypogenic processes operating along the saline water interface that may have been subsequently enlarged by lateral flows of fresh water undersaturated with respect to calcium carbonate. Moreover, analogous "mega-karst" in the Edwards (BFZ) recharge zone may represent earlier locations of hypogenic karst creation, implying that the entire Edwards (BFZ) system has gradually shifted downdip since Balcones faulting.

The Edwards (BFZ) Aquifers through the Neogene

Role of the Del Rio Clay Top-Seal

Most publications on the Edwards (BFZ) aquifers recognize that the presence of the Del Rio Clay controls the distribution of the Edwards (BFZ) artesian aquifer—it provides the upper confining layer without which the Edwards aquifer would not be artesian (Hovorka et al., 1996). What is surprising is that the role of the Del Rio Clay in the *evolution* of the Edwards (BFZ) aquifer has seemed to go unrecognized. Perhaps this reflects the common view of the Edwards (BFZ) aquifers as static.

For example, Abbott (1975, p. 260) suggested the artesian-saline water interface was created "as a bypass boundary that meteoric ground water moving under structural or hydrologic controls did not transgress. For example, groundwater moving toward the Comal Springs sink enlarged its initial flow paths, which once established, continued to grow. Originally the [saline water interface] was probably a random hydrologic flow boundary [that] has become deeply ingrained with time."

But the Del Rio outcrop along the present Balcones Escarpment, dipping gently southeastward, must have extended farther northwest in the geologic past; indeed, at the end of the Cenomanian, it probably extended 30–50 mi northwest (Fig. 20A) before pinching out in Edwards, Kimble, Gillespie and Blanco counties (Rose, 2016). There is no way of knowing now how much of the Del Rio was removed by erosion during the Late Cretaceous and Paleogene, or exactly where the updip edge of the Del Rio outcrop lay immediately after Balcones faulting. Assuming that, by the beginning of stage 2 (about 17.5 Ma), the updip edge of the Del Rio Clay lay a few miles updip (northwest) of the northernmost synthetic faults of the BFZ, across southern Bandera and southeastern Kendall and Blanco counties, the projected northern limit is compatible with the lithologic succession characteristic of the Plateau aquifer in interfluvial outcrops of the Edwards Group.

It is also possible to assume that wherever the updip edge of the Del Rio outcrop lay at any time after completion of Balcones faulting, the porous Edwards aquifer beneath it was artesian. The recharge zone lay northwest; the artesian zone lay southeast. Assuming that there was then a counterpart subsurface saline zone that extended basinward into the subsurface, an artesian/saline water interface must have separated them, where mixing of fresh and saline waters encouraged porosity development by hypogene processes. The first artesian/saline water interface likely coincided with the northernmost faults of the BFZ.

The Edwards (BFZ) Aquifers since Balcones Faulting

Abbott (1975) produced a compelling account of the evolution of the Edwards (BFZ) aquifer, to which Woodruff and Abbott (1986) related the geologic development of the BFZ landscape. Maclay and Small (1986) described and documented in detail the geology and hydrology of the Edwards Aquifer in the San Antonio area. Ellis (1985, 1986) described and discussed diagenesis of Edwards Group carbonate rocks in the BFZ. Hovorka et al. (1996) provided a thorough discussion of porosity/permeability types and probable processes that produced them.

Abbott (1975) and Woodruff and Abbott (1986) emphasized the importance of discharge points in the central sector of the BFZ artesian aquifer, notably San Marcos Springs, to provide for throughput of fresh waters that enhance existing cavernous and fracture porosity in transiting the artesian zone. All-important discharge points lie in the lowest surface elevations, i.e., river valleys—especially the Guadalupe, Comal, and San Marcos river valleys. Schindel and Gary (2018) agreed that the existence of strong springs as discharge points is essential for the continuing development of karstic permeability in the Edwards (BFZ) artesian zone. They saw the consistent decline in the elevation of major springs, southwest to northeast along the BFZ, as evidence of progressive evolution of the aquifer system. An alternative view starts with the recognition of the gentle regional slope of the entire Edwards (BFZ) artesian aquifer from west (Uvalde) to east (San Antonio) to northeast (San Marcos); the observed decline in elevation of strong springs may represent nothing more than the aforementioned regional structural decline of the aquifer system rather than an evolution and migration of strong springs in the same direction.

However, Schindel and Gary (2018) have usefully reintroduced the concept of an evolving Edwards (BFZ) aquifer system, as opposed to a static system, represented only by the configuration of the current Edwards (BFZ) aquifer. Consideration of the entire Edwards (BFZ) aquifer as an evolving system is encouraged by the recognition that the overlying Del Rio Clay, the confining top-seal of the Edwards artesian aquifer, has been undergoing erosion in a downdip (southeast) direction since the first occurrence of Balcones faulting 21 Ma. Accordingly, the underlying artesian aquifer zone must also have migrated downdip. Consequently, severely karsted Edwards strata now present in the recharge zone may have been in the artesian zone at an earlier stage. Moreover, their porosity may have first been enhanced when these carbonate rocks lay along the then saline water interface, where hypogenic processes and mixing of formation waters (Deike, 1990; Hovorka et al., 1996) created early porosity that was subsequently enlarged by undersaturated meteoric water. Finally, in an evolving system, the saline water interface would have shifted downdip (southeast) as part of the gradual migration of the entire aquifer system, downdip along the Balcones faultline escarpment.

Several million years may have passed before an early recharge zone formed, to provide a continuous and copious flow to the artesian zone, feeding pressured subsurface water along the saline interface, enhancing earlier hypogenic karstic porosity. If that hypothesis is correct, the entire recharge/artesian/saline complex has migrated southeastward perhaps 5–15 mi in about 18–19 Myr (Figs. 20A–20C).

CONCLUSION: NEOGENE EVOLUTION OF CENTRAL TEXAS LANDSCAPE AND GEOHYDROLOGY

Overview

There are four components in the geologic story of the evolution of the Central Texas landscape and geohydrology during and after Balcones faulting. They involve: (1) changes in the

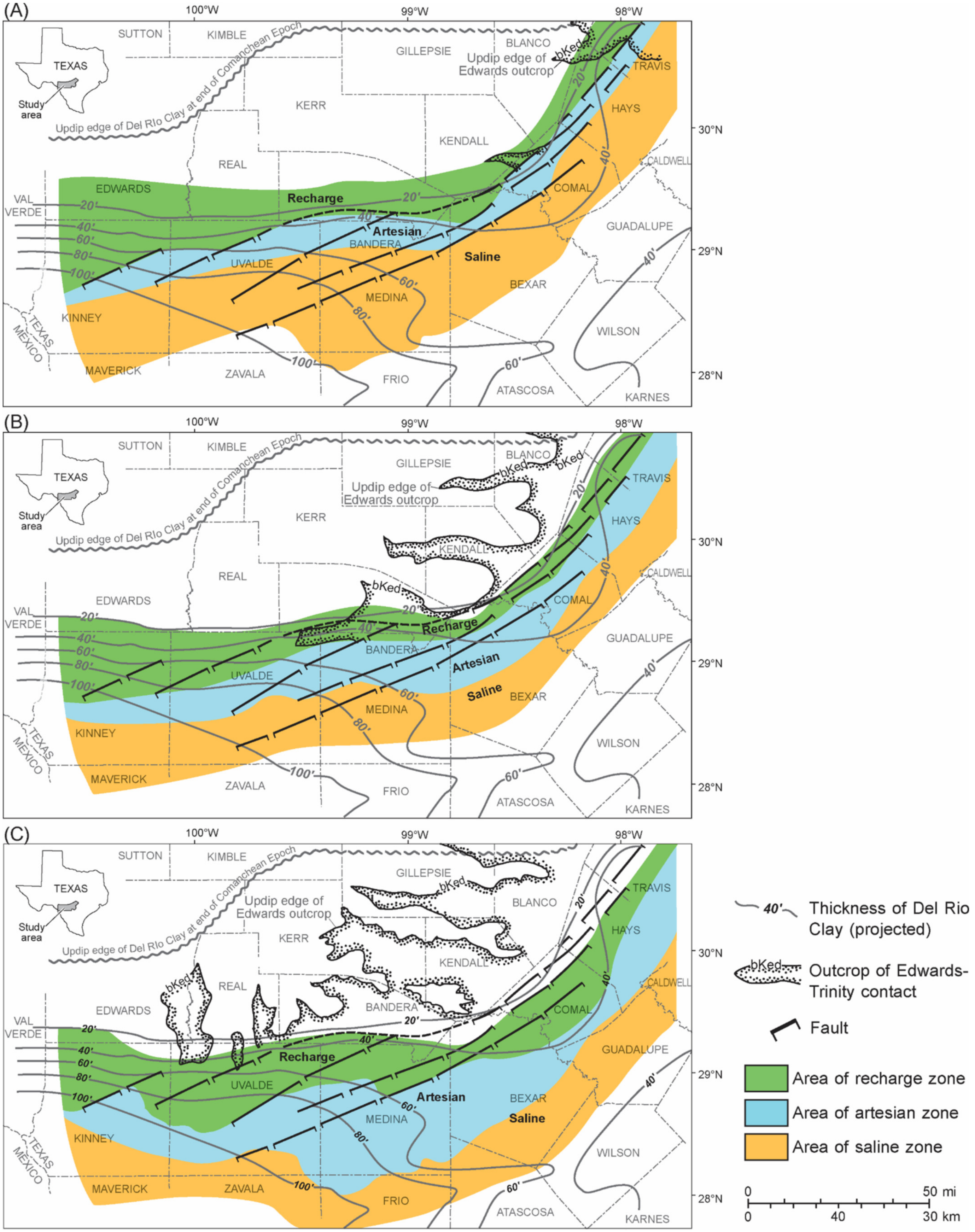

Figure 20. Map series showing southeastward migration of Edwards (BFZ) aquifer systems (recharge, artesian, and saline) after Balcones faulting (modified after Hovorka et al., 1996). (A) Hypothetical configuration of Edwards aquifer system in stage 2 (17.5–14 Ma). (B) Hypothetical configuration of Edwards aquifer system in stage 4 (10.5–7 Ma. (C) Actual configuration of Edwards aquifer system at present time.

drainage patterns of the Colorado and other river systems; (2) reduction of the surface area of the Edwards Plateau by headward erosion; (3) development, evolution, and downdip migration of the recharge, artesian and saline zones of the Edwards (BFZ) aquifer system; and (4) the lowering of the water table of the Edwards Plateau aquifer over time.

Conditions at the Onset of Balcones Faulting

During the 40 Myr from middle Paleocene to early Miocene, the area of the Central Texas Platform between the future BFZ and the Llano Dome began gradually to be uplifted above the Tertiary coastal plain. Upper Cretaceous chalks, marls, and mudstones overlying the Edwards Limestone were increasingly exposed and eroded (Rose, 2016) so that by early Miocene time (Fig. 17A), most of area north and west of the future BFZ was a low, flat limestone plain, exposed down to the resistant top of the Edwards Limestone, or the thin Del Rio/Buda succession overlying the Edwards. Erosional wedges of Austin and Taylor-Navarro strata may have extended a few miles northwestward from the faulted margins of the Plateau. Rainwater and runoff were able to charge the widespread unconfined Plateau aquifer in the lower part of the Edwards, but the aquitard at the base was probably not exposed, hence any natural springs were incidental, occurring wherever erosion by pre-Balcones streams happened to cut deeply enough to intersect the top of the Edwards water table. Such conditions were probably limited to the lower courses of main streams such as the Colorado, Pecos, and possibly the Guadalupe and Medina rivers. With a large surface area for recharge and limited discharge, the Edwards Plateau aquifer was at maximum thickness in its host, the Edwards Limestone. Fresh water in this aquifer graded downdip into brackish and saline waters probably along the trend of the future BFZ; mixing of fresh and saline water generated early hypogenic karst along a northeast-southwest arc that coincided roughly with the BFZ's updip edge.

Precursor streams bounded the Edwards Limestone plain: the ancestral Brazos and Pecos rivers on the northeast and west respectively, and the Rio Grande on the southwest. The antecedent Colorado River flowed from northwest to southeast across the limestone plain, moderately entrenched between the buried Llano Dome downstream to the future Mount Bonnell Fault. Shallow primary tributaries also probably existed, precursors of the present Concho, Pecan Bayou, San Saba, and Llano rivers, although the actual locations of their ancient stream courses are conjectural. Smaller counterpart early streams may have included the Pedernales, Guadalupe, Medina, and Nueces rivers. Meanders had been established in many of these precursor streams by middle Paleocene, in an arcuate belt marginal to, and inboard from, the future BFZ. With gentle uplift, such meanders began to entrench and propagate downward.

Phase 1 (21–14 Ma)

Earliest Balcones faults (~21 Ma) were down-to-the-coast normal faults along the west and north margins of the present BFZ. Subsequent adjustment faulting, both synthetlc and antithetic, occurred within a 20 mi wide swath mostly gulfward of the first faults; duration of the full episode of Balcones faulting is not known, but it may have spanned only a few million years, probably confined entirely to the years spanning phase 1 (21–14 Ma), or even to stage 1, the first 3.5 Myr after the onset of faulting.

The newly elevated limestone plain on top of the Edwards (and overlying thin Del Rio/Buda outliers) now formed the top of an east- and south-facing escarpment that immediately began to be dissected by existing streams as well as newly truncated former tributaries. These stream drainages now coalesced to form new downstream drainage systems that spread an apron of limestone detritus (the Miocene Oakville Formation) across the coastal plain downstream from, and opposite to, the new escarpment.

The Del Rio/Buda/ succession overlying the Edwards Group, in combination with abrupt structural downwarping along the BFZ, led to the formation of a robust artesian aquifer in the underlying Edwards Group. Responding to weathering and subaerial erosion, the Del/Rio/Buda outcrop began to migrate down the slope of the Balcones Escarpment. The saline water interface also gradually began to shift southeastward.

By the end of stage 1 (Fig. 15B), the southeastern and southern front of the newly elevated highland had been dissected into a series of short (10-20 mi,) high gradient canyons cut several hundred feet into the Edwards Limestone. These canyons were the precursors of the present Blanco, Guadalupe, Medina, Frio, Nueces and Devils rivers. Wherever the new canyons intersected Balcones faults, spring-flows began, some of which then entered underground fault-blocks of porous and fractured Edwards Group strata, eventually entering segments that were overlain by the impervious overlying Del Rio Clay, but continuing to flow downdip and along strike, under the influence of gravity. Undersaturated surface waters began to move through the thick Edwards Group carbonate strata, beginning to enlarge and modify earlier hypogenic karst. This was the beginning of the artesian Edwards (BFZ) aquifer. Its original location lay parallel to, and a few miles northwest of, its present updip edge. The artesian/saline water interface also continued its gradual shift southeastward. In the central and western sectors of the Edwards Plateau, it is possible that horizontal caves began to develop at lower levels as the water table of the Edwards Plateau aquifer began to decline, and spring-flow increased toward the end of phase 1.

During stage 2 (17.5–14 Ma), further headward erosion of the Edwards Limestone by the Nueces, Frio, Medina, and Guadalupe drainage systems more than doubled the width of the dissected Edwards Limestone terrane between the Balcones escarpment and the south-facing front of the receding Edwards Plateau. New, steep gradient streams pirated the stream-flow of previous streams, leading to increased dissection and further enhancement of coarse-textured porosity and permeability in carbonate strata, inherited from earlier hypogene karst processes along a precursor artesian/saline interface. These streams utilized and enlarged abundant fracture systems in the BFZ. In its lower course, only the Guadalupe River had now cut through the base of the Edwards, into the underlying Glen Rose formation. Flow volume of the Medina/San Antonio River system increased, thus augmenting recharge of the Edwards in the BFZ, thence into the Edwards artesian aquifer, enlarging passageways first created by hypogenic karstification. The artesian zone continued to shift gradually southeastward as its confining top-seal, the Del Rio Clay, was eroded along the face of the escarpment (Fig. 20A).

Farther northeastward, the Colorado River, previously an established low gradient stream, drained a wide area of the limestone plain to the northwest. Still confined within incised meanders in its lower course, the Colorado extended its gorge straight upstream (northwest) almost 100 mi from the newly formed Balcones escarpment. By the end of stage 1 (17.5 Ma), this gorge had cut through the Edwards Limestone to expose the aquitard at the base of the Edwards (bKed), initiating sustained and widespread spring flow from the Edwards Plateau aquifer. By the end of stage 2 (14 Ma), the Colorado River had extended its straight gorge 60 mi farther northwest and deeper, reaching downward near the base of Cretaceous strata. Its narrow inner canyon was flanked on either side by a broad valley bounded by cliffs of Edwards Limestone. Short tributaries extended themselves headward, precursors of the Concho, San Saba, Pecan Bayou, Llano, and Pedernales rivers.

Farther west, the Pecos River continued to carve its narrow, winding gorge between walls of massive Edwards Limestone; large-amplitude incised meanders characterized the lower reaches of the Pecos, as it approached the equally spectacular incised meanders of the Rio Grande. Thirty miles east, and roughly parallel to the Pecos, a short new stream, the Devils River, flowed southward, through inherited meanders, confined entirely within the upper measures of the Edwards Limestone.

Phase 2 (14–10.5 Ma)

The chief new geomorphic development of phase 2 was the lateral shift of the Colorado River about 35 mi eastward, to form its Great Bend (Fig. 15D). This migration began early in stage 3, when the Colorado cut downward through thin, soft Cretaceous sandstone formations underlying the Edwards Group, onto hard Paleozoic (Lower Pennsylvanian) limestone strata that dipped northeastward, diverting stream flow along their structural strike (Fig. 12), aided by stream piracy by a Pecan Bayou tributary. Eastward migration ceased when the Colorado River encountered, then took over, the southward stream course of Pecan Bayou. Farther southward, the Colorado River occupied the course of an earlier east-side tributary that had joined the Colorado River about 10 mi downstream from the mouth of the Llano River. This has been the course of the Colorado River, from near Marble Falls upstream to the head of Buchanan Lake, since the end of stage 3.

One of the main consequences of the Colorado's northeastward shift was to create a broad lowland southwest of the Great Bend, with a much wider host valley, as defined by bounding cliffs of Edwards Limestone. The Colorado River now ran along the northeastern side of its wide valley, close by the steep, confining Edwards Limestone wall. A second consequence was that this lateral migration truncated the Colorado's eastern tributaries. Its western tributaries extended eastward, following the east-shifting parent stream, but also continued to erode headward (west). This history now manifests itself by the present marked asymmetry of the Colorado River system, from the mouth of the Concho River downstream to the Mount Bonnell Fault at Austin: sparse, short tributaries on the east and long straight tributaries on the west.

The Colorado River and its main western tributary, the Llano River, cut through Cretaceous strata into the Precambrian crystalline rocks of the Llano Dome. By the end of stage 3, the Llano River ran in Precambrian bedrock from the mouth of the Llano River west across Llano County into adjoining Mason County. The Colorado River ran in Precambrian crystalline bedrock from the head of Buchanan Lake southward, well past the mouth of the Llano at Kingsland.

The ragged southern front of the Edwards Plateau retreated northward a few miles, widening the dissected limestone terrane between the top of the Plateau and the BFZ, and the young Devils River cut back northward into the Plateau, while still remaining entirely within the Edwards Limestone. As the surface area of exposed Edwards Limestone shrank, the top of the Edwards Plateau aquifer also declined, as evidenced by multiple levels of horizontal caves. To the west, the Pecos River continued to carve its narrow canyon between ever-rising walls of Edwards Limestone.

The Edwards (BFZ) recharge zone and artesian aquifer continued to shift gradually southeastward (downdip) as the overlying Del Rio Clay was eroded. Porosity and permeability gradually increased in the central sector of the artesian zone with continued ground-water flow, and the linked Edwards (BFZ) saline zone interface shifted with it. Hypogene karst processes continued to create porosity along the saline interface, presaging the linear porous lenses that characterize the BFZ artesian aquifer today (Figs. 19A and 19B).

Phase 3 (10.5 Ma–Present)

Phase 3 (stages 4, 5, and 6) is a simple story recording the gradual but relentless westward and northward retreat of the ragged escarpment marking the margins of the Edwards Plateau. With each successive stage, the eastern edge of the Plateau retreated another 20–30 mi farther west; the southern edge retreated another 10–20 mi farther north. The dissected limestone terranes east and south of the plateau's top became progressively wider, culminating in today's scenic Hill Country landscape. The valley of the Colorado River also widened, but always from the west, as the Colorado's course from Pecan Bayou to Austin remained pinned close against the cuesta on the western margins of the Lampasas Cut Plain.

Perhaps because the Edwards Limestone itself becomes thinner, more argillaceous, and thus less resistant to erosion northward from the Concho River (Rose, 2017), the largest area of removal of Edwards Limestone (thus shrinkage of the area of the Edwards Plateau) is in the drainage of the Concho River. It is also possible that the elevation of the top of the unconfined aquifer in the Edwards Limestone probably declined as dissection of the Plateau increased, the area of recharge shrank, and outflow from increasing numbers of headwater springs increased discharge from the Plateau aquifer as a whole.

The boundary between the Miocene and Pliocene is about 5.4 Ma (Berggren et al., 1995a, 1995b), in the middle of stage 5. No clear change is apparent in the evolution of the Plateau landscape that may correspond to the Miocene-Pliocene boundary.

As headward erosion and downcutting proceeded along the southern front of the Edwards Plateau during stages 4, 5, and 6, exposure of the base of the Edwards Limestone increased westwardly. Only two rivers continued to flow exclusively within the Edwards Limestone—the West Nueces and the Devils rivers.

In the central sector of the BFZ, the linked Edwards (BFZ) recharge/artesian/saline aquifers continued their gradual shift eastward and downdip, as the outcrops of the confining Del Rio top seal were eroded away (Fig. 20B). The adjacent saline-zone interface shifted with it, with hypogenic processes continuing to create early karst that was later enlarged by undersaturated fresh water. The subsurface position of the Edwards (BFZ) artesian aquifer gradually came to its present location as erosion of the Balcones Escarpment stabilized (Fig. 20C). The San Marcos Springs became the chief exit-point for waters of the central sector of the (BFZ) artesian aquifer.

We do not know when the Medina Arch began to rise along the southeastern margins of the Edwards Plateau. About 60 ft of north dip is apparent at the Base Edwards mapping surface (bKed) (Rose, 1972), and 250 ft of north dip is shown (Rose, 2016) on top Edwards (tKed), but some of this relates to southward stratigraphic thickening, especially of the Segovia Formation, the upper cycle of the Edwards Group. But the configuration of the Medina Arch is congruent with, and inboard from, the BFZ. Furthermore, all streams that show a concave-upward stream profile originate from the area of the Medina Arch, suggesting that it is still active, thus it probably postdates the BFZ.

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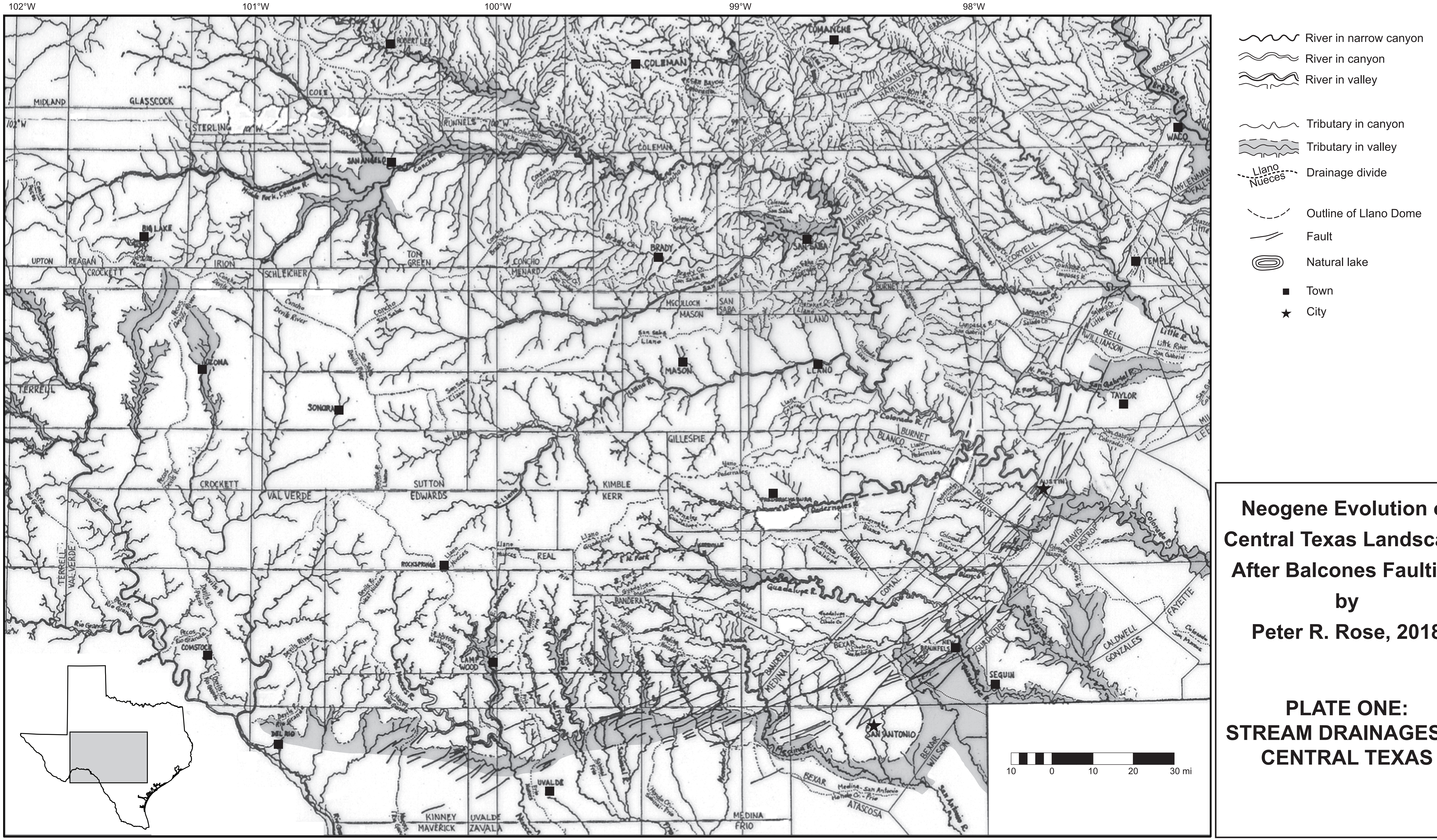
APPENDIX

This Appendix includes two plates that are included in the digital version of this paper (Digital Plates 1 and 2). Digital Plate 1 illustrates the drainage basins of Central Texas rivers. Digital Plate 2 illustrates the stream profiles of 12 Texas rivers: 1, Colorado River; 2, Concho River; 3, San Saba River; 4, Llano River; 5, Pedernales River; 6, Blanco River; 7, Guadalupe River; 8, Medina River; 9, Frio River; 10, East Nueces River; 11, West Nueces River; and 12, Devils River.



Neogene Evolution of Central Texas Landscape After Balcones Faulting

by

Peter R. Rose, 2018

PLATE ONE: STREAM DRAINAGES IN CENTRAL TEXAS

Neogene Evolution of Central Texas Landscape After Balcones Faulting
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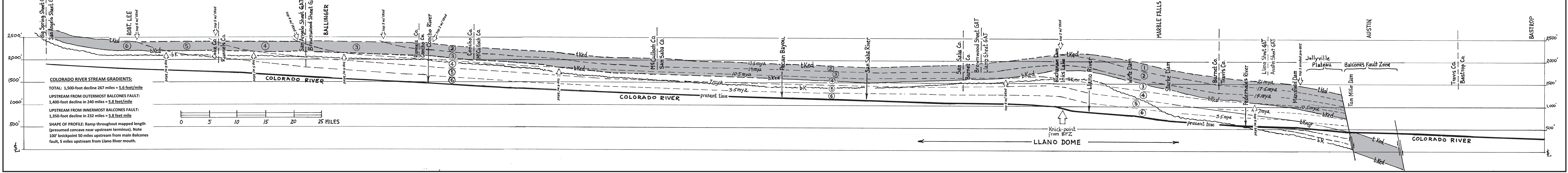
PLATE TWO: STREAM PROFILES OF CENTRAL TEXAS RIVERS

Profile #1: Colorado River



COLORADO RIVER STREAM GRADIENTS:

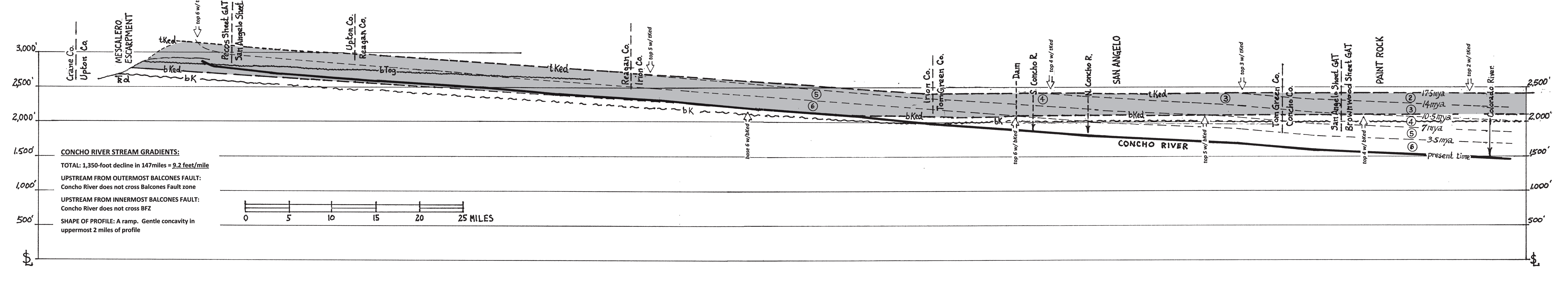
TOTAL: 1,500-foot decline 267 miles = 5.6 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: 1,400-foot decline in 240 miles = 5.8 feet/mile

UPSTREAM FROM INNERMOST BALCONES FAULT: 1,350-foot decline in 232 miles = 5.8 feet mile

SHAPE OF PROFILE: Ramp throughout mapped length (presumed concave near upstream terminus). Note 100' knickpoint 50 miles upstream from main Balcones fault, 5 miles upstream from Llano River mouth.

Profile #2: Concho River



CONCHO RIVER STREAM GRADIENTS:

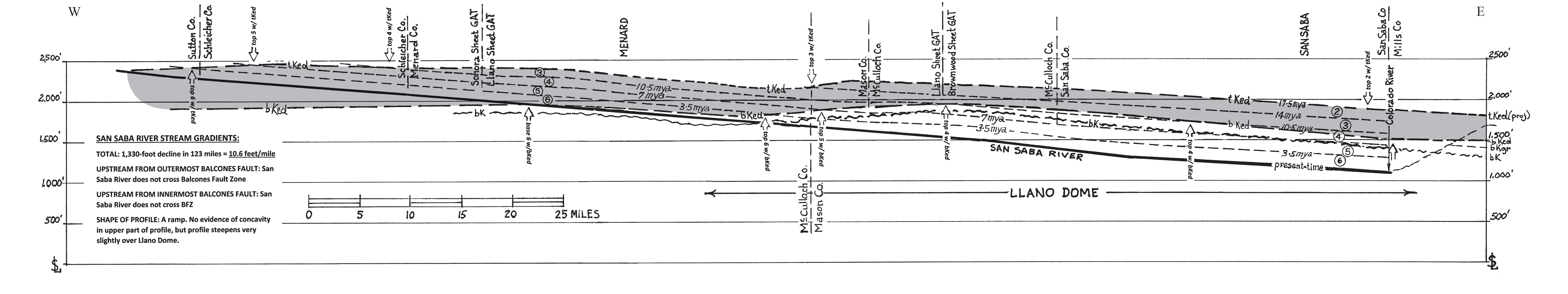
TOTAL: 1,350-foot decline in 147miles = 9.2 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: Concho River does not cross Balcones Fault zone

UPSTREAM FROM INNERMOST BALCONES FAULT: Concho River does not cross BFZ

SHAPE OF PROFILE: A ramp. Gentle concavity in uppermost 2 miles of profile

Profile #3: San Saba River



SAN SABA RIVER STREAM GRADIENTS:

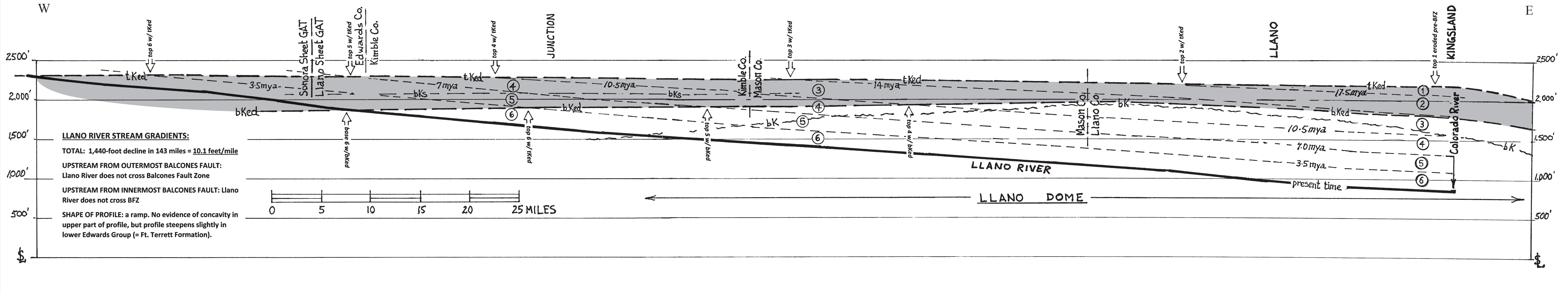
TOTAL: 1,330-foot decline in 123 miles = 10.6 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: San Saba River does not cross Balcones Fault Zone

UPSTREAM FROM INNERMOST BALCONES FAULT: San Saba River does not cross BFZ

SHAPE OF PROFILE: A ramp. No evidence of concavity in upper part of profile, but profile steepens very slightly over Llano Dome.

Profile #4: Llano River



LLANO RIVER STREAM GRADIENTS:

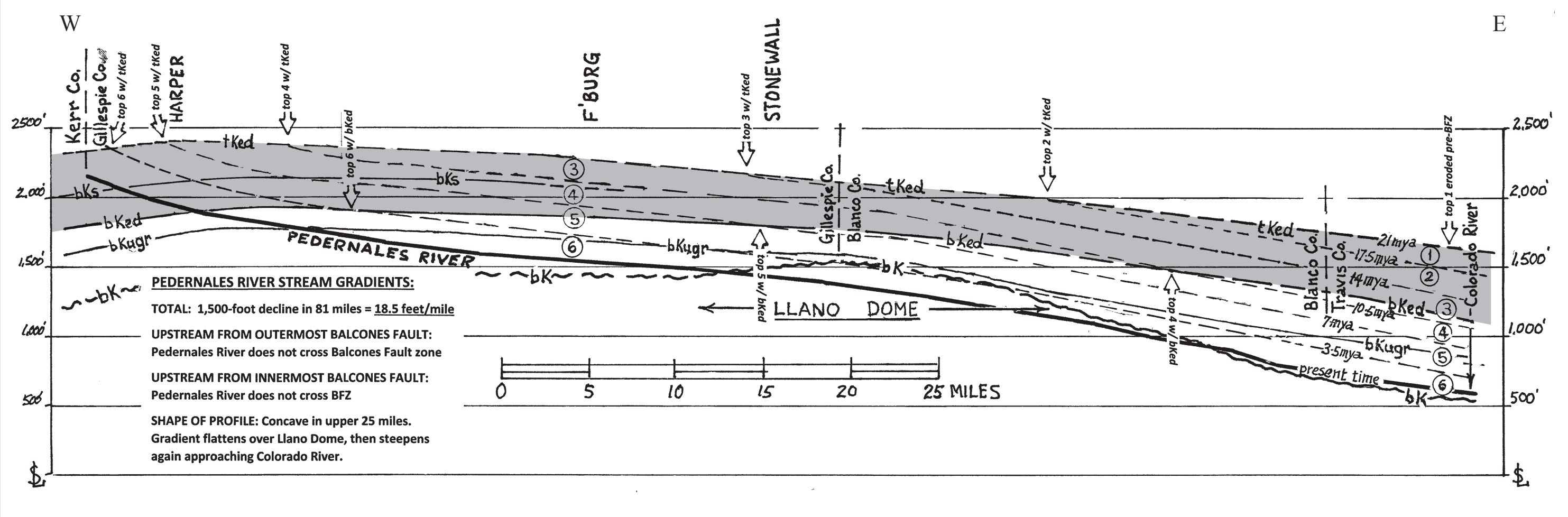
TOTAL: 1,440-foot decline in 143 miles = 10.1 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: Llano River does not cross Balcones Fault Zone

UPSTREAM FROM INNERMOST BALCONES FAULT: Llano River does not cross BFZ

SHAPE OF PROFILE: a ramp. No evidence of concavity in upper part of profile, but profile steepens slightly in lower Edwards Group (= Ft. Terrett Formation).

Profile #5: Pedernales River



PEDERNALES RIVER STREAM GRADIENTS:

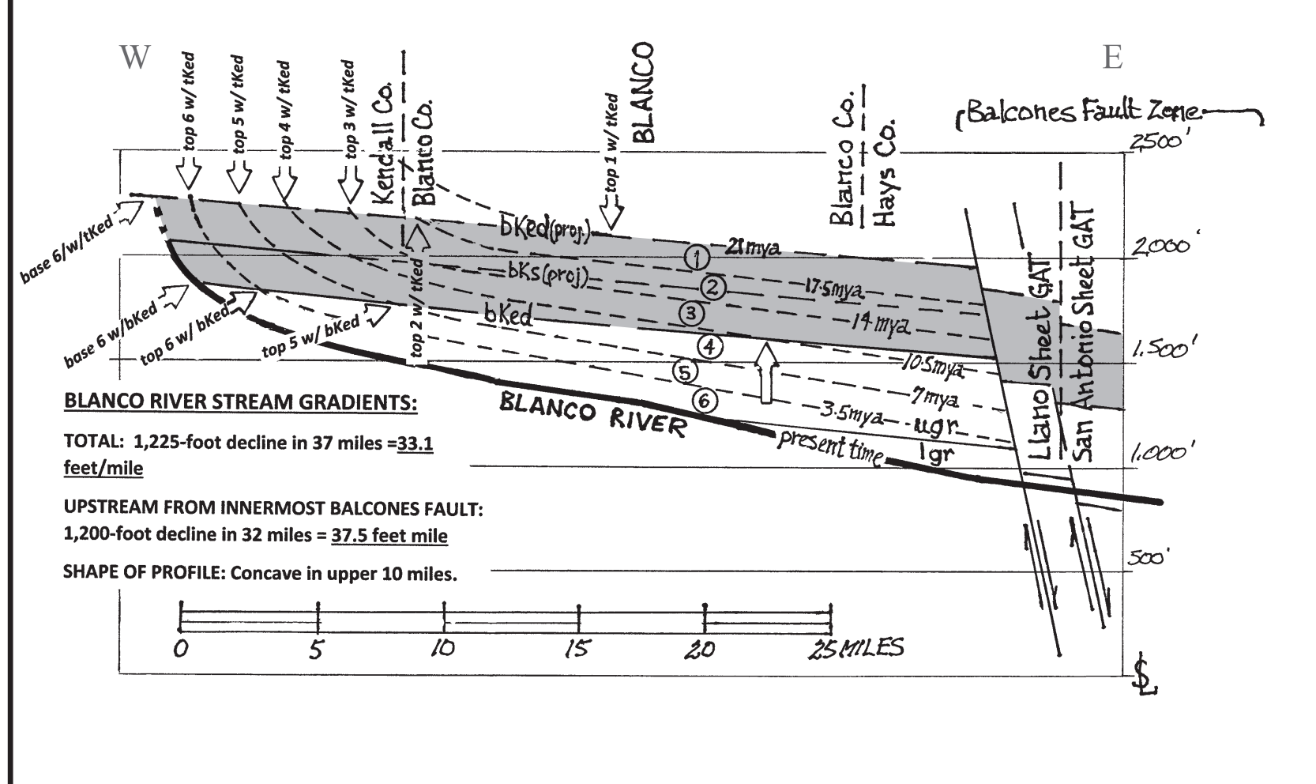
TOTAL: 1,500-foot decline in 81 miles = 18.5 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: Pedernales River does not cross Balcones Fault zone

UPSTREAM FROM INNERMOST BALCONES FAULT: Pedernales River does not cross BFZ

SHAPE OF PROFILE: Concave in upper 25 miles. Gradient flattens over Llano Dome, then steepens again approaching Colorado River.

Profile #6: Blanco River



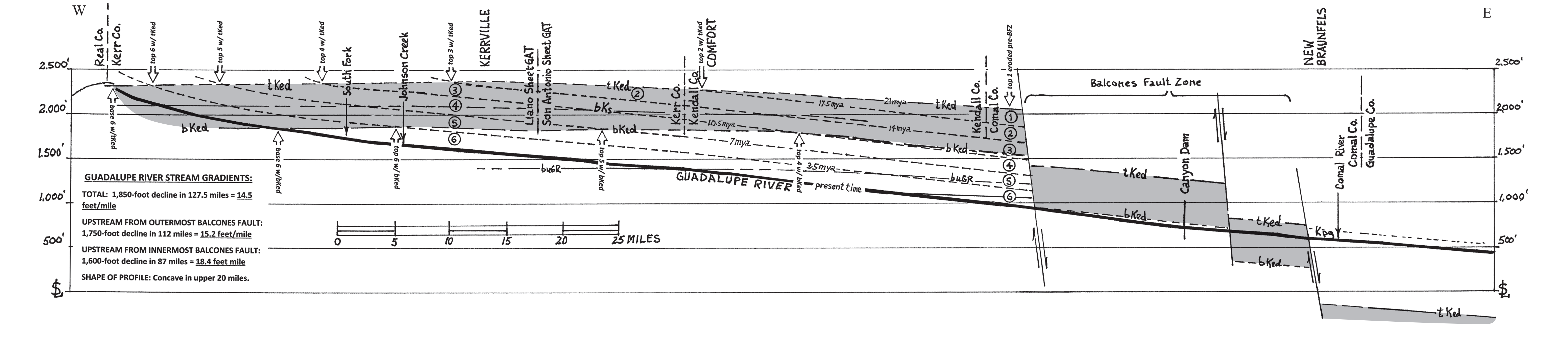
BLANCO RIVER STREAM GRADIENTS:

TOTAL: 1,225-foot decline in 37 miles = 33.1 feet/mile

UPSTREAM FROM INNERMOST BALCONES FAULT: 1,200-foot decline in 32 miles = 37.5 feet mile

SHAPE OF PROFILE: Concave in upper 10 miles.

Profile #7: Guadalupe River



GUADALUPE RIVER STREAM GRADIENTS:

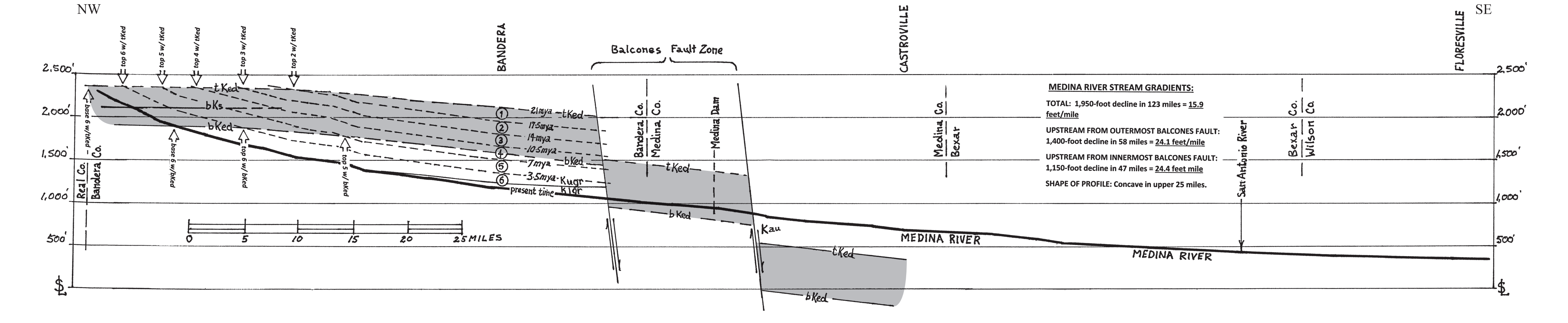
TOTAL: 1,850-foot decline in 127.5 miles = 14.5 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: 1,750-foot decline in 112 miles = 15.2 feet/mile

UPSTREAM FROM INNERMOST BALCONES FAULT: 1,600-foot decline in 87 miles = 18.4 feet mile

SHAPE OF PROFILE: Concave in upper 20 miles.

Profile #8: Medina River



MEDINA RIVER STREAM GRADIENTS:

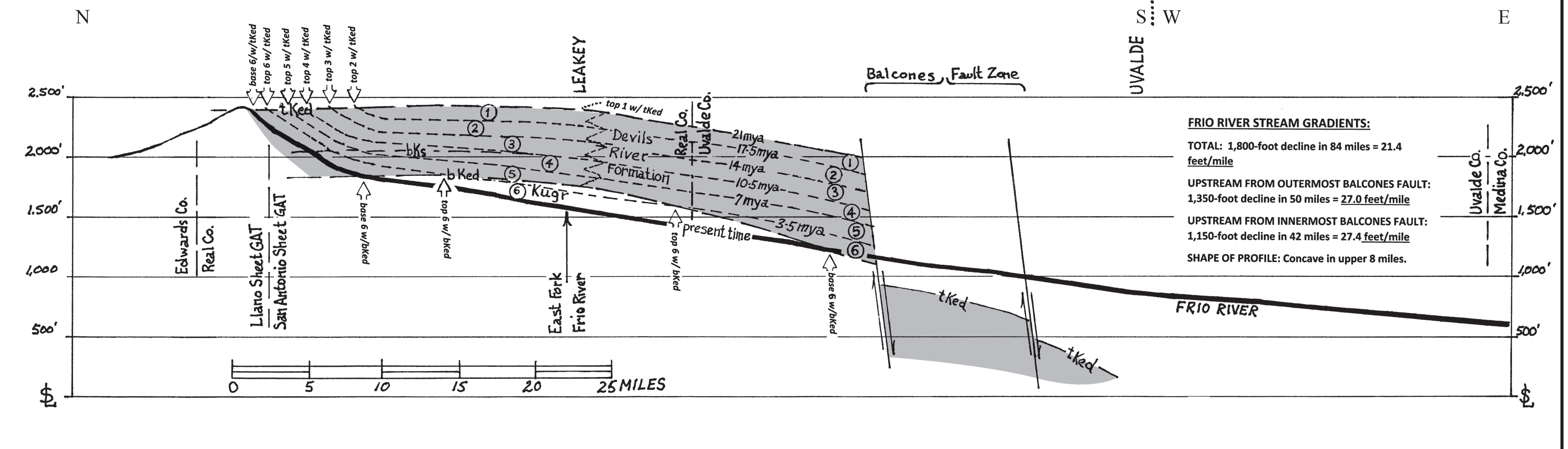
TOTAL: 1,950-foot decline in 123 miles = 15.9 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: 1,400-foot decline in 58 miles = 24.1 feet/mile

UPSTREAM FROM INNERMOST BALCONES FAULT: 1,150-foot decline in 47 miles = 24.4 feet mile

SHAPE OF PROFILE: Concave in upper 25 miles.

Profile #9: Frio River



FRIO RIVER STREAM GRADIENTS:

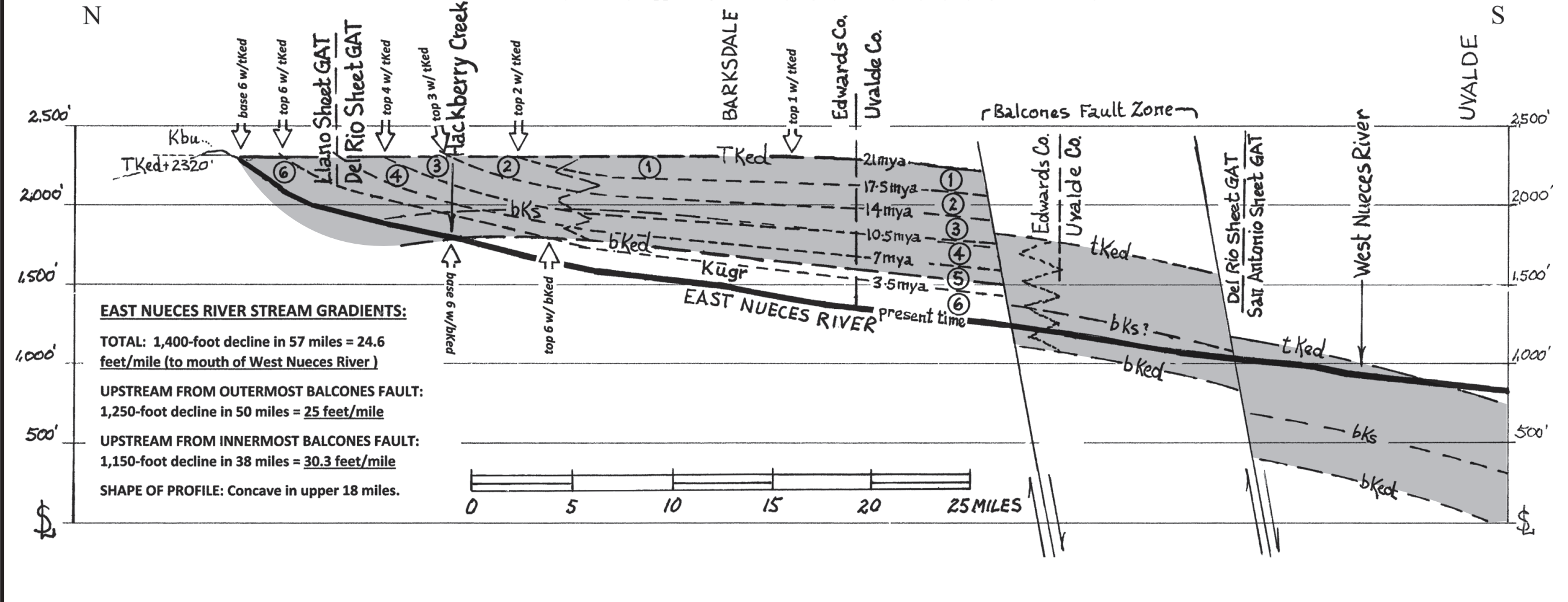
TOTAL: 1,800-foot decline in 84 miles = 21.4 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: 1,350-foot decline in 50 miles = 27.0 feet/mile

UPSTREAM FROM INNERMOST BALCONES FAULT: 1,150-foot decline in 42 miles = 27.4 feet/mile

SHAPE OF PROFILE: Concave in upper 8 miles.

Profile #10: East Nueces River



EAST NUECES RIVER STREAM GRADIENTS:

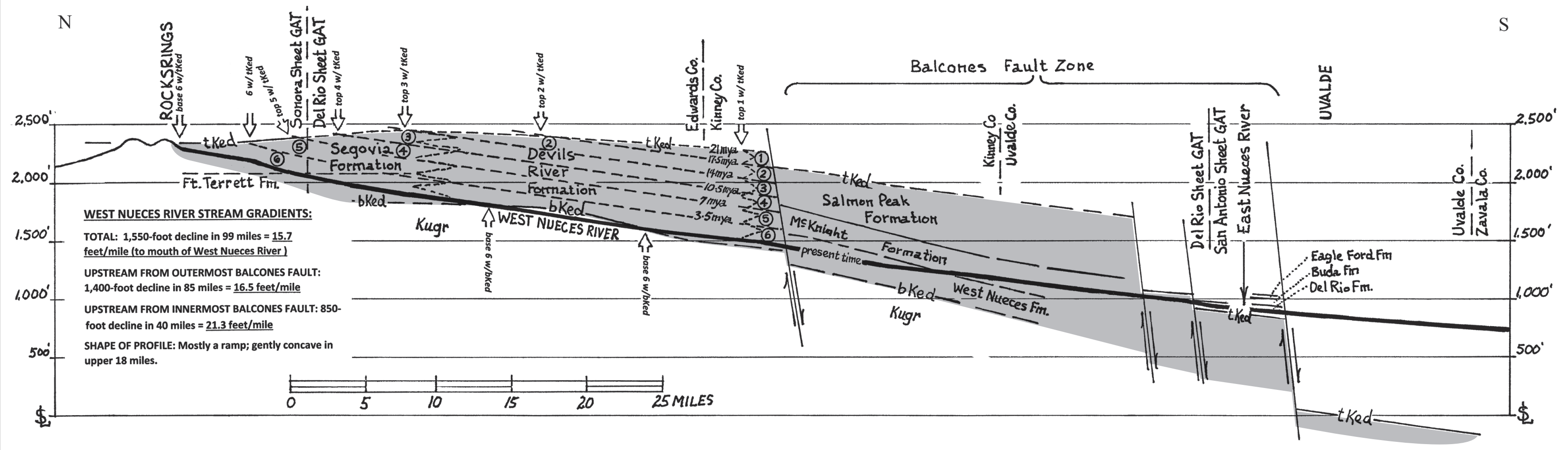
TOTAL: 1,400-foot decline in 57 miles = 24.6 feet/mile (to mouth of West Nueces River)

UPSTREAM FROM OUTERMOST BALCONES FAULT: 1,250-foot decline in 50 miles = 25 feet/mile

UPSTREAM FROM INNERMOST BALCONES FAULT: 1,150-foot decline in 38 miles = 30.3 feet/mile

SHAPE OF PROFILE: Concave in upper 18 miles.

Profile #11: West Nueces River



WEST NUECES RIVER STREAM GRADIENTS:

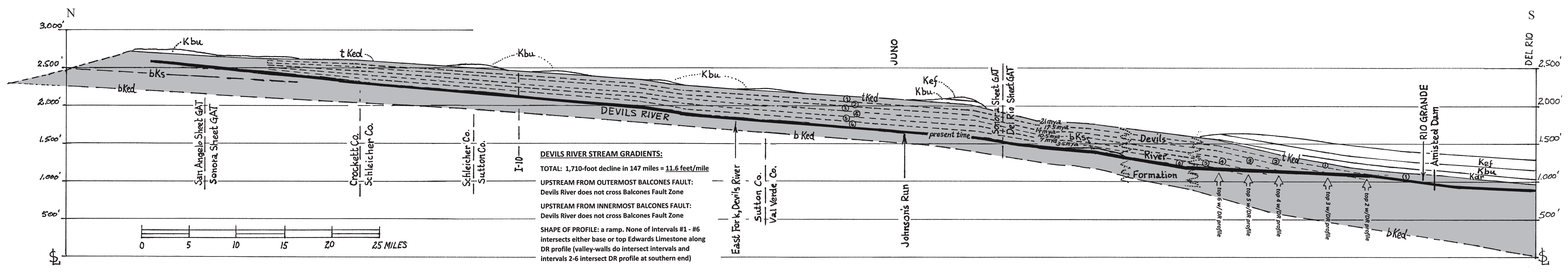
TOTAL: 1,550-foot decline in 99 miles = 15.7 feet/mile (to mouth of West Nueces River)

UPSTREAM FROM OUTERMOST BALCONES FAULT: 1,400-foot decline in 85 miles = 16.5 feet/mile

UPSTREAM FROM INNERMOST BALCONES FAULT: 850-foot decline in 40 miles = 21.3 feet/mile

SHAPE OF PROFILE: Mostly a ramp; gently concave in upper 18 miles.

Profile #12: Devils River



DEVILS RIVER STREAM GRADIENTS:

TOTAL: 1,710-foot decline in 147 miles = 11.6 feet/mile

UPSTREAM FROM OUTERMOST BALCONES FAULT: Devils River does not cross Balcones Fault Zone

UPSTREAM FROM INNERMOST BALCONES FAULT: Devils River does not cross Balcones Fault Zone

SHAPE OF PROFILE: a ramp. None of intervals #1 - #6 intersects either base or top Edwards Limestone along DR profile (valley-walls do intersect intervals and intervals 2-6 intersect DR profile at southern end)