History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin

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ABSTRACT

The Cenozoic fill of the Gulf of Mexico basin contains a continuous record of sediment supply from the North American continental interior for the past 65 million years. Regional mapping of unit thickness and paleogeography for 18 depositional episodes defines patterns of shifting entry points of continental fluvial systems and quantifies the total volume of sediment supplied during each episode. Eight fluvio-deltaic axes are present: the Rio Bravo, Rio Grande, Guadalupe, Colorado, Houston-Brazos, Red, Mississippi, and Tennessee axes. Sediment volume was calculated from digitized hand-contoured unit thickness maps using a geographic information system (GIS) algorithm to sum volumes within polygons bounding interpreted North American river contribution. General age-dependent compaction factors were used to convert calculated volume to total grain volume. Values for rate of supply range from >150 km to <10 km³/Ma.

Paleogeographic maps for eleven Cenozoic time intervals display the evolving matrix of elevated source areas, intracontinental sediment repositories, known and inferred drainage elements, and depositional fluvial/deltaic depocenters along the northern Gulf of Mexico basin margin. Patterns of sediment supply in time and space record the complex interplay of intracontinental tectonism, climate change, and drainage basin evolution. Five tectono-climatic eras are differentiated: Paleocene late Laramide era; early to middle Eocene terminal Laramide era; middle Cenozoic (Late Eocene–Early Miocene) dry, volcanogenic era; middle Neogene (Middle–Late Miocene) arid, extensional era; and late Neogene (Plio–Pleistocene) monsoonal, epeirogenic uplift era. Through most of the Cenozoic, three to four independent continental-scale drainage basins have supplied sediment to the Gulf of Mexico.

INTRODUCTION

The Gulf of Mexico (GOM) originated as a small ocean basin created by seafloor spreading in the Middle Jurassic through Early Cretaceous. By the end of the Mesozoic, mixed carbonate and clastic sedimentation had constructed a northern basin margin characterized by a broad coastal plain and shelf fronted by a well-defined shelf edge and continental slope (Galloway, 2008). However, clastic sediment supply rates were low, in part because of the high global sea levels that characterized the Cretaceous and in part because the Gulf basin was insulated from sediment derived from the active Laramide foreland uplands by the intervening foreland basin seaway that extended from Canada to northern New Mexico. Beginning in the late Paleocene, large volumes of terrigenous clastic sediment began to enter the basin from continental North America, constructing large fluvial/deltaic systems along an extensive, prograding continental margin (Galloway, 2008). Along this margin, loading of stretched continental crust caused broad flexural down warping, creating accommodation space for an inboard apron of coalesced alluvial plain deposits, forming the upper coastal plain (Galloway, 1981). This apron merged basinward with a mosaic of delta plain and shore-zone systems that together constructed the lower coastal plain. Seaward and beneath the prograding lower coastal plain succession, a prism of continental slope deposits, 5–10 km thick, infilled the deep basin (Galloway, 2008). Basinal deposits, also several kilometers thick, derived from the northern continental margin lap out against the Yucatan Platform to the south and the Florida Platform to the east and mix with sediments of the eastern Mexican continental slope to the west.

Galloway (2005b) spliced the depositional record of the northern GOM to the interpreted regional tectonic, climatic, and geomorphic history of the continental interior to produce a synthesis of North American drainage basin evolution. Since that effort, several advances in our understanding both of North American Cenozoic history (source) and of the GOM depositional record (sink) combine to create the opportunity for a more accurate and detailed synthesis.

(1) New synthesis papers have elucidated the regional history and timing of Cenozoic deposition and erosion within the continental interior (Holm, 2001; Raynolds, 2002; Flores, 2003; Cather, 2004; Sewall and Sloan, 2006; Cather et al., 2008; Chapin, 2008; Smith et al., 2008; Davis et al., 2009; Lawton et al., 2009).

(2) Regional tectonic syntheses have provided quantitative information about the timing and location of volcanic activity, uplift, and erosional unroofing of source uplands (McMillan et al., 2002; Chapin et al., 2004a; Kelley and Chapin, 2004; McMillan et al., 2006; McDowell, 2007; Eaton, 2008; Flowers et al., 2008; Cather et al., 2009; Fan and Dettman, 2009).

(3) Deep petroleum exploration drilling and seismic data acquisition on the GOM continental slope and abyssal plain has resolved the correlation of seismic sequences of the deep basin with basin margin depositional episodes (e.g., Combellas-Bigott and Galloway, 2005; Radovich et al., 2007).

(4) Regional seismic depth sections have provided thickness information where well control is lacking, allowing construction basin-wide isopach contour maps that can be used for volumetric calculations (Galloway et al., 2000; Galloway, 2002).

(5) Ongoing mapping of GOM genetic sequences incorporating new well, seismic, and published information has continued to enhance paleogeographic map detail for Cenozoic depositional episodes (Galloway et al., 2000; Galloway, 2008).

The combination of information from these diverse resources offers the opportunity to update, quantify, and significantly enhance

paleogeographic resolution of the 65 Ma Cenozoic history of this continental scale source–sink couple. That is the objective of this paper.

Volume and Volume Rate of Sediment Supply

Following the stratigraphic framework of Galloway et al. (2000), GOM Cenozoic strata were divided into 18 chronologically significant depositional episodes (deposodes) for mapping and volumetric analysis (Fig. 1). Each deposode was a significant period of sediment supply and continental margin growth. Each is recorded in the deposits of regionally correlative genetic sequences (Galloway, 1989; Catuneanu et al., 2009) that are bounded by major transgressive beds and contained maximum flooding surfaces. These flooding events punctuated the dominantly progradational history of the continental platform on the northern basin margin. For purposes of this analysis, the relatively high-frequency deposodes of the Plio-Pleistocene are grouped into two composite deposodes of 2–3 Ma duration. This makes them more comparable to the remaining 13 deposodes, which average ca. 5 Ma in duration.

Methodology

A GIS database containing nearly 2000 points (wells and depth-converted seismic shot points; see the Appendix) was used to manually contour an isopach map of each genetic sequence. The manual contours were then closely replicated using the Topo To Raster tool, a standard Spatial Analyst tool for ArcGIS (©2006, ESRI). A key feature of the tool is that it takes both points (well and shot point data values) and contours as input for use in its interpolation of the output thickness grid. The area for volume calculation was defined by a polygon consisting of zero-value contours (preserved or projected depositional limits; lap-out boundaries) and boundaries that exclude areas of the basin fill consisting dominantly of (1) autochthonous carbonate sediment or (2) terrigenous clastic sediment derived from western GOM source areas in central and southern Mexico. The output raster, depicting thickness of the unit, is multiplied by cell size (selected to be 1 km), giving volume computed in cubic kilometers using standard ArcMap functionality. Summed volumes for the point grid yield a total volume for the sequence (Table 1). The complete methodology is described in the Appendix.

To further standardize rate comparisons and better approximate actual sediment supply to the Gulf, general porosity values for sediments of differing ages (and consequently averaged depth of burial and degree of compaction) derived for similar volume calculations in the Atlantic margin by Pazzaglia and Brandon (1996) were used to recalculate total volumes of solids (grain volume) for each sequence. These generalized porosity values attempt to account for the greater compaction of older (and thus more deeply buried) sediments relative to younger (shallower) sediments. They are not lithology specific, and subsume the variable mix of sandstone and mudstone. They are approximations that improve final grain volume estimates.

Results

Results of volumetric calculations are summarized in Table 1. Of most interest is the grain volume rate column. This value estimates the average rate that solid mineral matter was deposited in the basin during each of 14 differentiated geologic time intervals (Liu and Galloway, 1997). Extreme time spans of 1 and 10.6 Ma likely accentuate and subdue, respectively, calculated values. However, the other 12 time steps cluster between 3 and 6.6 Ma, providing a relatively consistent standard for rate calculation.
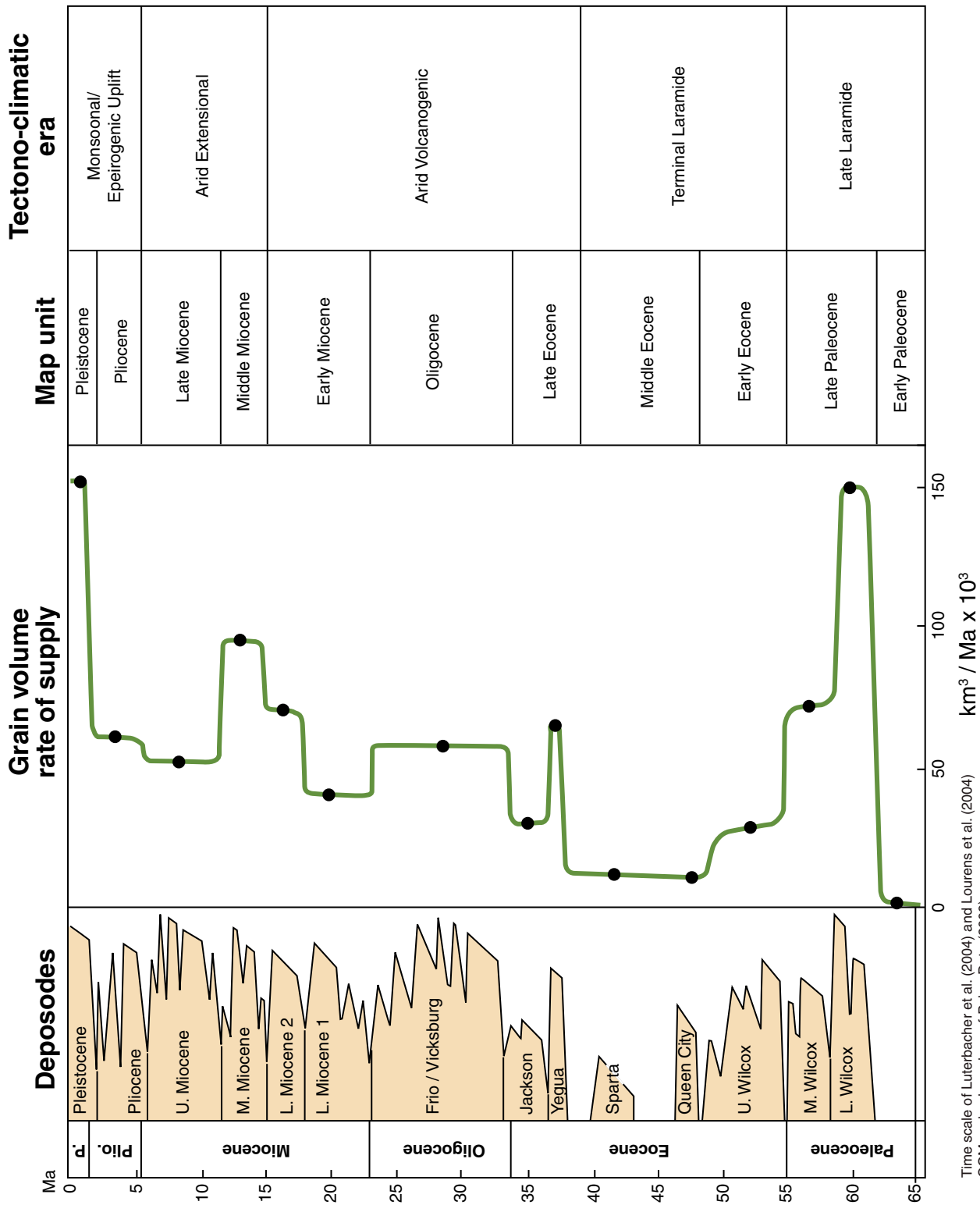
Initial deposition across the northern GOM began with a 3 Ma phase of sediment starvation. This interval corresponds to a thin, marine mud rock unit named Midway or Porters Creek Formation across the outcrop belt and in the subsurface. The interval is condensed throughout the deep basin. Because it is not differentiated from the overlying Wilcox Group in the most deep subsurface correlation, total volume and derivative values were not calculated. Values would, however, clearly be much lower than any seen in the overlying 14 intervals. Following this period of sediment starvation, supply increased abruptly in the Late Paleocene with deposition of the Lower Wilcox sequence. Grain volume rates exceeded 150,000 km³/Ma—the highest seen in any multi–million-year deposode. High rate of sediment supply caused rapid progradation of major delta and accompanying shore-zone systems to the shelf edge, extensive depositional offlap of the continental slope, and accumulation of a composite family of thick, sand-rich abyssal plain fan systems on the GOM basin floor (Galloway et al., 2000; Zarra, 2007).

There then followed a series of Late Paleocene through Middle Eocene deposodes with progressively decreasing grain volume rates of supply, culminating in the Sparta (SP) deposode. Latest Paleocene Middle Wilcox sediment influx rates were about one half those of the Lower Wilcox (Table 1). After a brief but extensive transgressive flooding of the northern

GOM continental platform associated with the Late Paleocene Thermal Maximum at ca. 55 Ma (Zachos et al., 2008), Wilcox deposition terminated with the long-lived Upper Wilcox deposode. Further reduction in sediment supply to ~25 km³/Ma was accompanied by long-term retrogradation of the central GOM coastal systems and early Eocene sediment starvation of the previously active abyssal fan systems (Galloway et al., 2000; Zarra, 2007). Carroll et al. (2006) document a comparable decrease in sediment supply and corresponding evolution from over-filled Paleocene to underfilled lacustrine Eocene deposition in the northern basins of the Western Interior. They attribute the observed decrease to removal of easily eroded Cretaceous foreland basin clastics and exposure of granitic cores of Laramide uplifts.

For nearly ten million years, encompassing much of the Middle Eocene, sediment supply to the northern GOM was extremely low. Only thin coastal and shelf facies prograded onto the northern shelf platform of the GOM. Extensive condensed intervals, including the glauconitic Weches and Cook Mountain Formations, extended from the inner coastal plain outcrop belt to the abyssal plain. This great period of GOM depositional quiescence ended abruptly with coastal progradation to and over the relict continental margin of the short-lived late Eocene Yegua (in Louisiana, Cockfield) deposode. Sediment supply rates increased more than sixfold above middle Eocene background values (Table 1). Following this initial late Eocene spurt, however, rates again declined by about half during the latest Eocene Jackson deposode.

The Paleogene history of the Gulf ended with a very long lived (10.6 Ma) Oligocene deposode known in the subsurface as the Vicksburg and overlying Frio formations. Averaged rate for this longest of the tabulated deposodes exceeds 55,000 km³/Ma, a robust value that presages those of the overlying Neogene stratigraphy (Table 1). Accumulation rate calculations of Galloway and Williams (1991, their fig. 5) for the northwest GOM margin suggest that rates were highest in the first several million years of the deposode and declined in the later Oligocene. This is consistent with the observation of long-term retrogradational transgression (forming the widespread Anahuac marine shale wedge) across the northern GOM margin. The value shown here averages these high initial values with low terminal values of this undifferentiated 10+ Ma deposode, thus reflecting neither extreme. Sediment supply rates were sufficiently high to support extensive Oligocene progradation of the entire northern GOM continental margin (Galloway, 2005a).

Figure 1. Chronology of Cenozoic depositional episodes (deposodes). Plot shows changing grain volume of sediment supply rate through time. Map unit column lists the time steps for which paleogeographic maps have been compiled. The Cenozoic drainage basin history can be grouped into five tectono-climatic eras as shown in the right-hand column. Time scale and deposodes modified from Galloway et al. (2000). The time scale is that of Luterbacher et al. (2004) and Lourens et al. (2004).

Time scale of Luterbacher et al. (2004) and Lourens et al. (2004)
GOM cycle chronology of Paleo-Data (2009)

TABLE 1A. CALCULATED TOTAL VOLUME, GRAIN VOLUME, VOLUME RATE, AND GRAIN VOLUME
RATE FOR EACH OF 14 DEPOSITIONAL EPISODES THAT COMPRISE THE GOM BASIN FILL

Deposode	Volume	Duration	Vol. rate	Porosity	Grain vol.	Grain vol. rate
Pleist.	822000	2.3	357391	0.6	328800	142,957
Plio.	509000	3.8	133947	0.55	229050	60,276
U. Mio.	455000	4.8	94792	0.45	250250	52,135
M. Mio.	476000	3.1	153548	0.4	285600	92,129
L. Mio. 2	364000	3.2	113750	0.4	218400	68,250
L. Mio. 1	347000	5.2	66731	0.4	208200	40,038
Olig.	920000	10.6	86792	0.35	598000	56,415
U. Eo. JS	113000	2.3	49130	0.3	79100	34,391
U. Eo. YC	161000	1.8	89444	0.3	112700	62,611
M. Eo. SP	72000	4.6	15652	0.3	50400	10,957
M. Eo. QC	85000	5.6	15179	0.3	59500	10,625
L. Eo. UW	248000	6.8	36471	0.3	173600	25,529
U. Pal. MW	349000	3.6	96944	0.25	261750	72,708
U. Pal. LW	664000	3.3	201212	0.25	498000	150,909

Note: JS–Jackson; YC–Yegua; SP–Sparta; QC–Queen City; UW–Upper Wilcox; MW–Middle Wilcox;
LW–Lower Wilcox. Units—km³ and Ma.

TABLE 1B. SAME DATA GROUPED TO CORRESPOND TO THE 10 TIME INTERVALS SHOWN
ON PALEOGEOGRAPHIC MAPS (FIGS. 7, 9–15, AND 17–19)

Deposode	Volume	Duration	Vol. rate	Porosity	Grain vol.	Grain vol. rate
Pleist.	822000	2.3	357391	0.6	328800	142,957
Plio.	509000	3.8	133947	0.55	229050	60,276
U. Mio.	455000	4.8	94792	0.45	250250	52,135
M. Mio.	476000	3.1	153548	0.4	285600	92,129
L. Mio.	711000	7.5	94800	0.4	426600	56,880
Olig.	920000	10.6	86792	0.35	598000	56,415
U. Eo.	274000	4.1	66829	0.3	191800	46,780
M. Eo.	157000	10.2	15392	0.3	109900	10,775
L. Eo.	248000	6.8	36471	0.3	173600	25,529
U. Paleoc.	1013000	6.9	146812	0.25	759750	110,109

Note: Units—km³ and Ma.

Lower Miocene stratigraphy of the northern GOM records two distinct deposodes, called lower Miocene 1 and 2 (LM 1 and LM 2) here. Each is of several million years duration. LM 1 displays the lowest grain volume rates observed in the Neogene (Table 1); however, the values are still robust, and the GOM margin actively prograded. The rate increased substantially during LM 2 deposition, approaching 70,000 km³/Ma. Middle Miocene rates again increased, exceeding 90,000 km³/Ma and obtaining values not seen since the Lower Wilcox deposode. Following the Miocene trend of continuously increasing rate of sediment supply, the upper Miocene deposode reflects a dramatic drop to a bit over 50% of the preceding middle Miocene peak.

Pliocene sediment supply rates remained high, approximating upper Miocene grain volume rate values (Table 1). Pleistocene values more than double. Although this may be partially a product of the shorter time span of the Pleistocene relative to the Pliocene, it reflects the global pattern of extreme rates of supply to Pleistocene ocean basins (Molnar, 2004). Pleistocene values of more than 140,000 km³/Ma match those of the late Paleocene. Uncorrected volume rates nearly double those of the Paleocene reflecting the fact that assumptions about bulk porosity and consequent compaction correction determine the "winner" in terms of grain volume rate of supply to the GOM basin. Regardless, the supply history is clearly bimodal, with peaks at the beginning and end of the Cenozoic basin fill history.

RECEIVING BASIN PALEOGEOGRAPHY: FLUVIAL/ DELTAIC AXES

Regional paleogeographic mapping of the northern GOM Cenozoic depositional episodes demonstrates that a relatively small number of continental-scale fluvial axes delivered the bulk of the sediment to the basin (Galloway et al., 2000; Galloway, 2005a, 2008). Each major fluvial axis created a major prograding deltaic depocenter and is further defined by the large scale of fluvial channel fill deposits seen in outcrop and the shallow subsurface. An informal nomenclature for these recurrent fluvial/deltaic axes, modified slightly from earlier publications, is shown in Figure 2. Eight axes are differentiated. From northwest to east, across the northern GOM coastal plain, the fluvial axes are named Rio Bravo, Rio Grande, Guadalupe, Colorado, Houston-Brazos, Red, Mississippi, and Tennessee. Fluvial axis nomenclature was chosen to reflect similarities in entry point along the Gulf margin, inferred location of the trunk stream, and/or drainage basin paleogeography to comparable attributes of modern extra-basinal fluvial systems.

Beginning in the northwest basin margin, the Rio Bravo axis reflects the Spanish name, Rio Bravo del Norte, for the international boundary river. The ancient drainage basin was similar to modern drainage elements, now tributary to the Rio Grande, in Chihuahua, Coahuila, and Nuevo Leon states. Its entry point lies south of the international boundary, in Tamaulipas. The Rio Grande axis has a long history (Fig. 3); it is characterized by its entry point across the South Texas coastal plain, somewhat north of its Quaternary position. Its headwaters have had diverse origins, ranging from Arizona to southern Colorado, at different times. The Guadalupe axis of the central Texas coastal plain was primarily active during the Miocene. Its locus approximates that of the modern Guadalupe, but its drainage basin extended northwest to extra-basinal sources. The Colorado axis is defined mainly by its interpreted drainage basin, which was an enlarged and extended version of its modern counterpart. It was a Laramide era drainage system that was important during the three Wilcox deposodes (Fig. 3). The Houston-Brazos axis reflects middle Cenozoic fluvial river systems that entered the GOM coastal plain at or northeast of the modern Brazos River. The Red axis was defined by its drainage basin development, generally comparable to that of the Quaternary Red River, and by its locus in southeast Texas (Fig. 2). It is a Neogene feature. The Mississippi axis is the most consistently present fluvial/deltaic depocenter of the northern Gulf margin. The Tennessee is a young Neogene fluvial axis defined by a drainage basin location coincident, in part, with that of its modern counterpart. Neither the Red nor Tennessee axes were tributary to the Mississippi as now; their permanent capture by the Mississippi Valley is a geologically recent phenomenon (Saucier, 1994).

Typically three or more major extra-basinal fluvial systems were active during any one deposode. In addition to pictorially summarizing the timing and duration of each fluvial axis, Figure 3 portrays the relative importance of each axis as a supplier of sediment to the GOM basin. The width of the bar is based on isopach depocenter volume and magnitude (rate and area) of continental margin progradation associated with each axis (Galloway, 2005a, 2002).

CONTINENTAL GEOLOGIC AND PHYSIOGRAPHIC FRAMEWORK

The physiography of the North American continental interior assumed its modern configuration during Cenozoic time. Concomitantly, a drainage network evolved to remove both runoff and entrained sediment from a land area
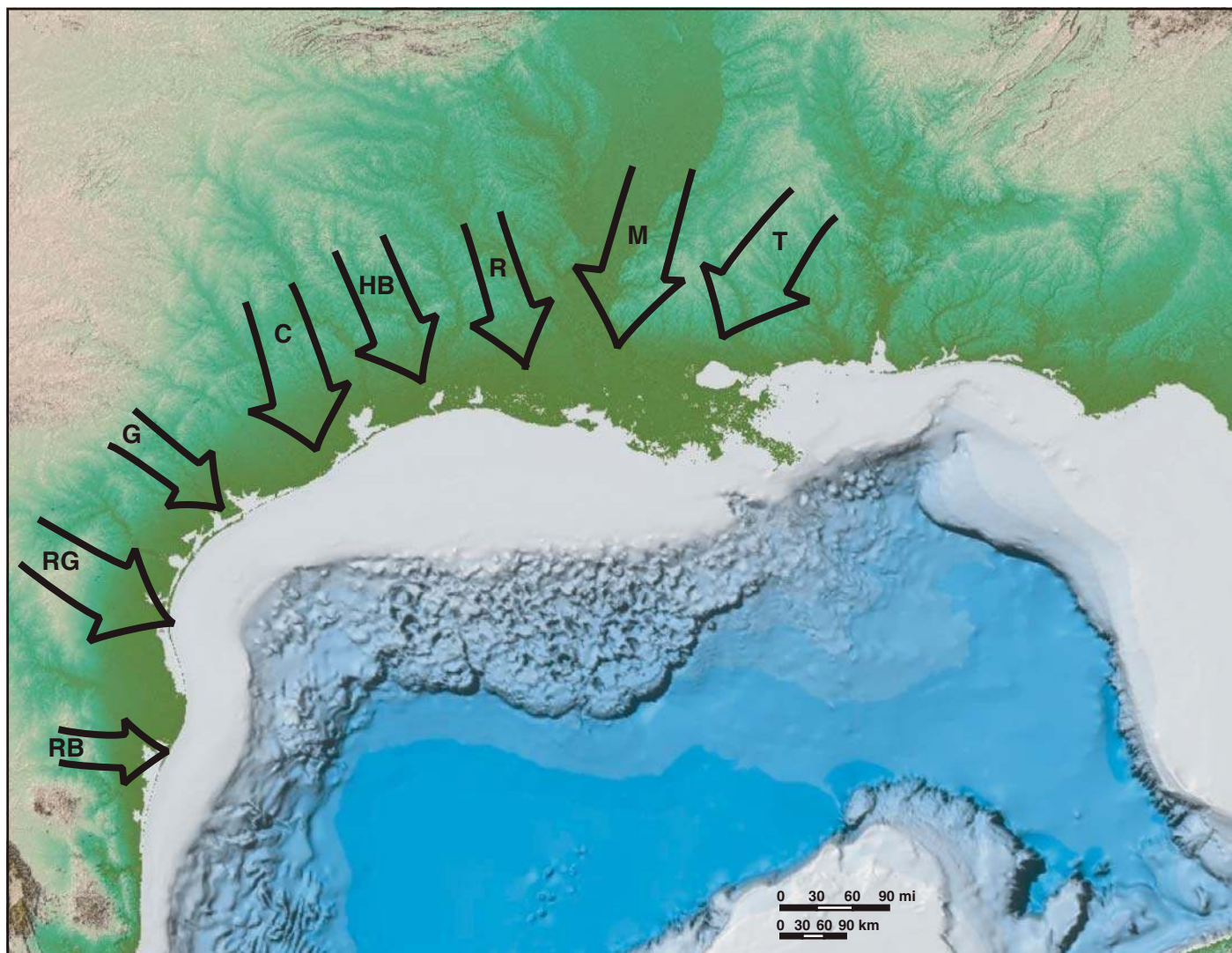
Figure 2. Geographic location of the Cenozoic fluvial input axes around the northern Gulf margin. Modified from Galloway (2008). RB–Rio Bravo; RG–Rio Grande; G–Guadalupe; C–Colorado; HB–Houston-Brazos; R–Red; M–Mississippi; T–Tennessee.

measuring 1500 × 2500 km (1000 × 1500 mi). Residual uplands, relicts of the late Paleozoic Appalachian orogeny, formed the eastern flank. A more complex and evolving array of tectonically active uplands lay to the west. Continental drainage divides separated streams flowing west or east into the Pacific or Atlantic from those converging into the low-relief continental interior. On the south was a mature divergent continental margin with a broad depositional coastal plain. A generally poorly documented drainage divide separated rivers flowing south into the GOM from those flowing north into the remnant embayment of the Cretaceous seaway or northeast into Baffin Bay.

Modern physiography reflects two principal orogenic phases. The Laramide orogenic phase, a continuation late Mesozoic tectonism, was a major compressional era that extended from Paleocene through the middle Eocene. It was followed by the Middle–Late Cenozoic phase of crustal heating, igneous activity, and extension.

Principal Laramide phase upland provinces potentially supplying sediments to the early Cenozoic GOM included (Fig. 4):

(1) Relict highlands of the Appalachian system, composed of the Blue Ridge Mountains, Ridge and Valley province, and Cumberland/ Allegheny Plateaus.

(2) Exposed remnants of the Ouachita system, a west-trending extension of the Appalachians, including the Ouachita Mountains, and the Marathon uplift.

(3) Late Laramide basement-cored uplifts extending from southern Montana southward to New Mexico. The eastern Laramide uplands

have remained topographically high to very high throughout the entire Cenozoic. Elevations have ranged between 2 and 3 km (Chase et al., 1998; McMillan et al., 2006; Eaton, 2008).

(4) The Sevier orogenic belt of the western interior United States.

(5) The Laramide fold and thrust belt of Mexico.

(6) The Mogollon highlands of southern Arizona.

(7) Relict uplands of the Chihuahua tectonic belt.

(8) The Colorado Mineral Belt and Absaroka volcanic uplands.

A major tectonic reorganization in the middle Cenozoic that included the Basin and Range extension and regional crustal heating, uplift, and volcanism, remolded the western North

American source provinces. Principal uplands produced include (Fig. 5):

(1) The Basin and Range province of block-faulted uplands and adjacent basins, extending southward from Idaho through northern Mexico.

(2) The Sierra Madre Occidental volcanic field of Mexico and outliers in the southwestern United States.

(3) The San Juan, Central Colorado, Marysvale, and numerous smaller volcanic fields of the Western Interior.

(4) The regionally elevated Neogene Rocky Mountain Orogenic Plateau, which is highest in central Colorado.

(5) The Colorado Plateau, a moderately high, structurally stable upland separating the Rocky Mountain Orogenic Plateau and the Basin and Range Province.

(6) The comparatively low-relief Edwards Plateau of central Texas.

Each orogenic phase also produced a family of basins within continental North Amer-

ica. These basins provided collectors for upland tributaries and alluvial fans, acted as temporary or permanent sediment repositories, and influenced the location and flow direction of axial, integrated fluvial systems. Late Laramide basins were particularly abundant (Fig. 4). They form an assemblage of small- to medium-sized depressions between and flanking the basement-cored uplifts. To the south, extending from the Big Bend area of Texas, narrow, elongate foreland subsidence belt including the Sabinas,
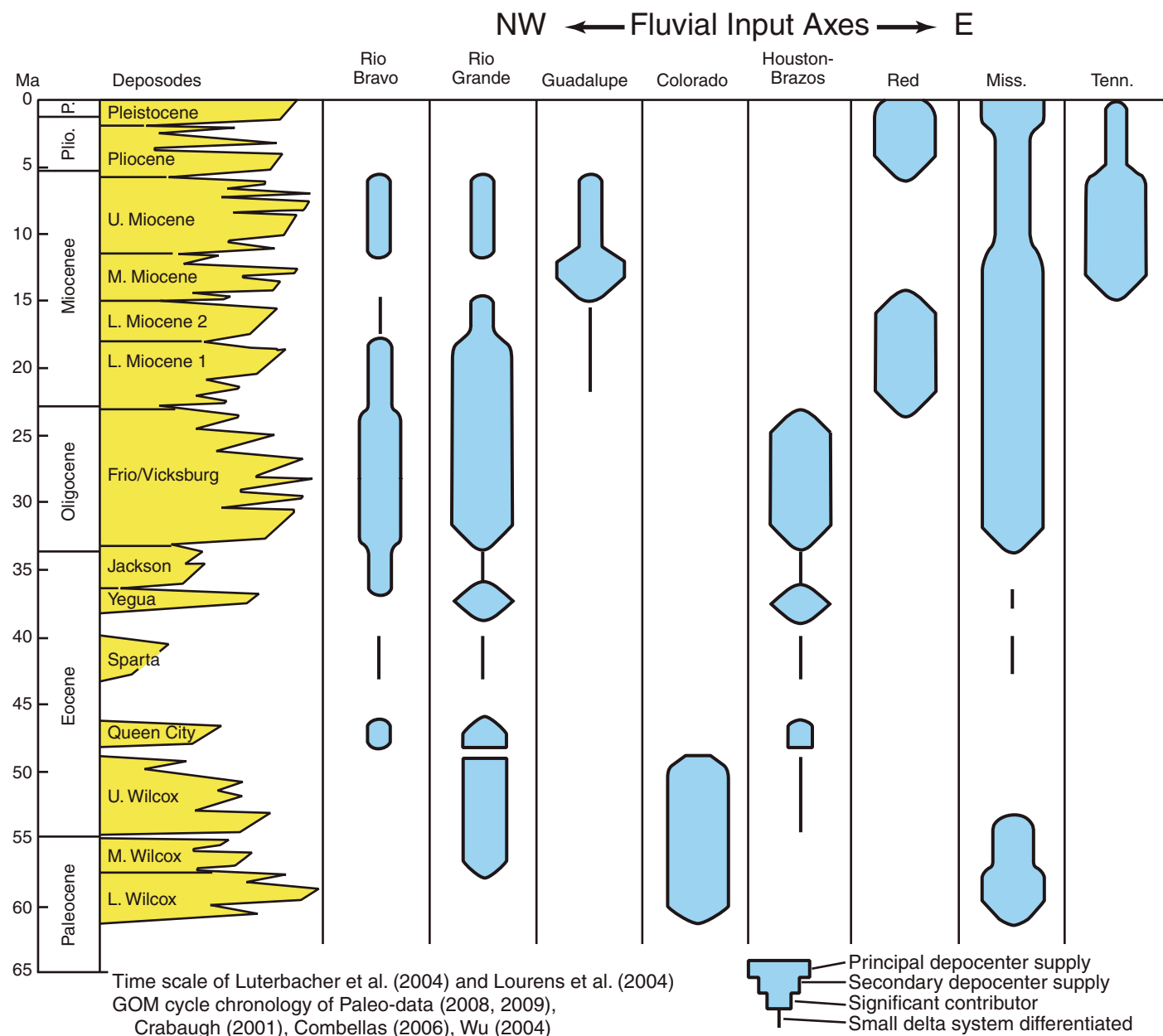

Figure 3. Temporal history of the eight extra-basinal fluvial input axes of the northern Gulf of Mexico basin margin. Axes are arranged according to geographic position from northwest (Rio Bravo) to northeast (Tennessee). The relative importance of each axis is schematically indicated by the width of the blue bar. Fluvial axes are informally named based on similarities in their location along the Gulf margin or of their inferred drainage basin in the continental interior.
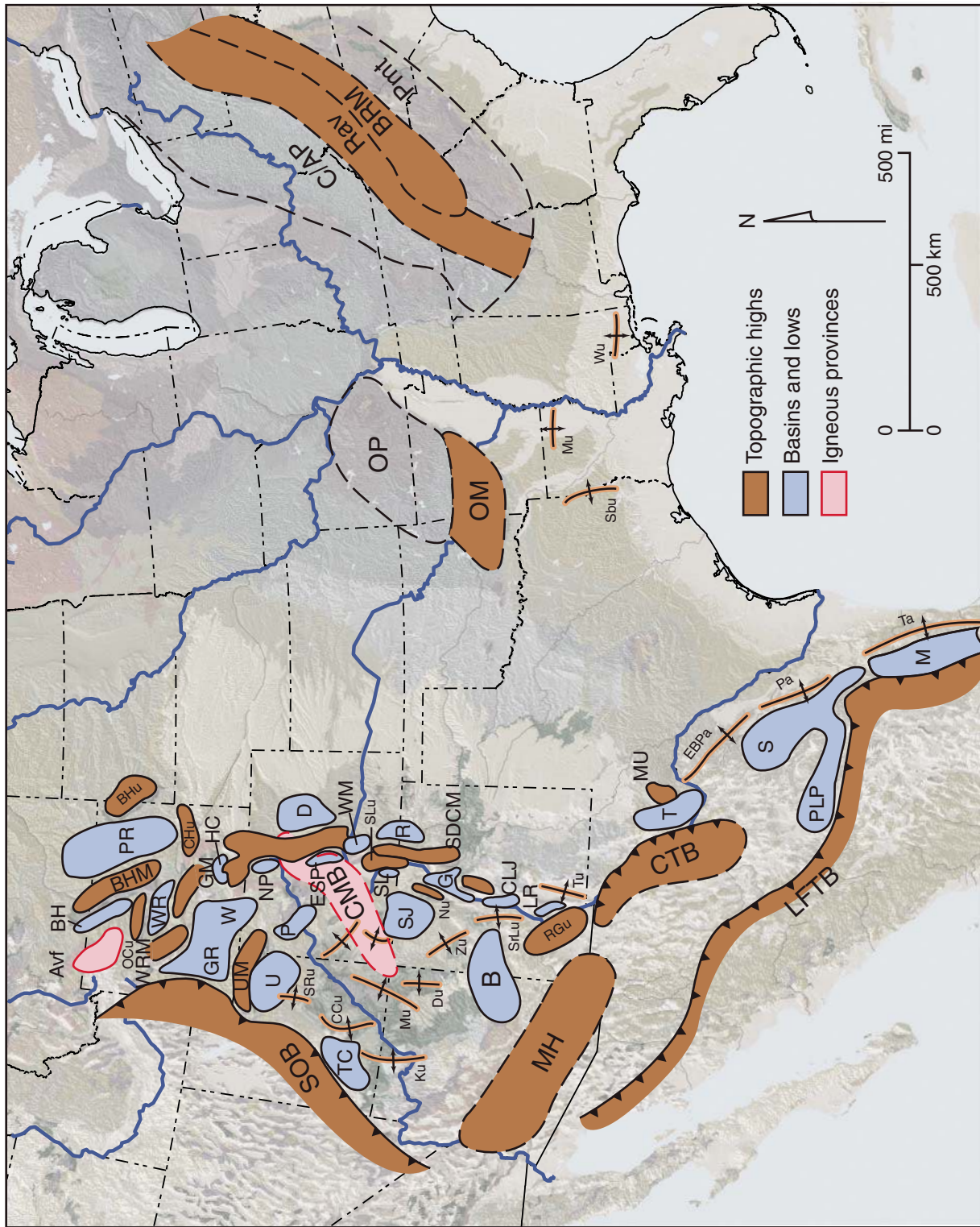
Figure 4. Principal structural and topographic elements of the Paleocene–Eocene Laramide era continental interior of North America. Brown color locates topographic uplands. Most are products of structural uplift or rejuvenation during Laramide deformation phases in the Paleocene and early Eocene. Some elements are relict topographic uplands of late Paleozoic origin. Blue polygons outline basins and topographic lows that were actively subsiding and accumulating sediment during at least part of the Laramide phase. For explanation of abbreviations, see Tables 2 and 3. Elements compiled from Tweto (1975), Dickinson et al. (1988), and Cather (2004). Base is the North America Tapestry of Time and Terrain (USGS, 2003).

Figure 5. Principal structural and topographic elements of Oligocene–Neogene continental interior of North America. The Basin and Range structural province (light green) formed the western margin of the interior province. Light brown areas broadly outline regionally elevated provinces that were actively eroded during the Neogene. For explanation of abbreviations, see Tables 2 and 3. Elements compiled from Christiansen and Yeats (1992), Perkins and Nash (2002), Cather (2004), Chapin et al. (2004a, 2004b), F. M. McDowell (2007, personal commun.), Cather et al. (2008), and Eaton (2008). Base is the North America Tapestry of Time and Terrain (USGS, 2003).

Parras–La Popa, and Magiscatzin basins was separated from the adjacent GOM by a chain of arches that together constitute the peripheral bulge. In contrast, middle–late Cenozoic basins east of the Basin and Range province itself were few. A series of extensional troughs connected to form the larger Rio Grande Rift, extending from central Colorado almost to the Big Bend area of Texas (Fig. 5).

EVOLVING CONTINENTAL PALEOGEOGRAPHY

The final goal of this discussion is to relate the depositional elements and history of the northern Gulf of Mexico basin (the sink) to the evolving North American interior tectonic and climatic framework (the source).

Drainage Basin Paleogeography Maps

Evolution of North American interior paleogeography and drainage systems is summarized in a suite of 11 maps (Fig. 1) compiled on the North America Tapestry of Time and Terrain base (USGS, 2003). Most of the maps display regional paleogeography for a single GOM deposode (e.g., Early Paleocene, Early Eocene, Oligocene, Middle Miocene, Late Miocene) or for two combined deposodes (e.g., Late Paleocene, Middle and Late Eocene, Early Miocene). High-frequency glacioeustasy and detailed chronology made possible by high-resolution paleontology result in the recognition of multiple Pliocene and Pleistocene deposodes in the GOM. These are grouped to show the general paleogeographic and depositional patterns that characterize and differentiate the Pliocene (pre-North American Ice Sheet) and Pleistocene (North American Ice Sheet). Each map displays a suite of paleogeographic elements as summarized in Tables 2 and 3. Figure 6 provides the explanation for the color scheme employed on the paleogeographic maps.

Maps were compiled from a variety of sources. The depositional basin paleogeography is based on Galloway et al. (2000) and Galloway (2008). General paleoclimate data were abstracted from Scotese (2009, www.scotese .com/climate.htm). For all maps, the greatest uncertainty exists in the connections across the central and southern continental interior lowlands, Mississippi Valley, and southeastern Appalachians, where little or no Cenozoic sedimentary record exists. In some units, distinctive petrologic constituents or bulk composition help connect specific fluvial/deltaic axes to tributary sources. Other interpreted connections are simply logical interpolations.

Drainage Basin Paleogeographic Evolution

Overview of Cenozoic interior North American geologic evolution suggests differentiation of five broad *tectono-climatic eras* (Fig. 1). Each is reflected by a relatively homogeneous tectonic framework, paleoclimate pattern, and consequent pattern of source areas, trunk fluvial transport systems, and depositional history. From oldest to youngest, they are:

(1) Paleocene late Laramide era: Active Laramide deformation created a family of subsiding basins and adjacent basement-cored uplands. The climate framework included an orographic tropical monsoonal belt along the east side of the Front Range, a subtropical Western Interior, a warm, subarid, seasonal southwest, and a cool temperate northern Western Interior.

(2) Early to Middle Eocene terminal Laramide era: Final pulses of Laramide deformation were followed by an extended period of tectonic stability, upland erosion, and alluvial aggradation. Climate remained warm and seasonally wet, becoming drier toward the northern Western Interior. Early Paleogene stratigraphic records of major tributary systems to GOM-flowing rivers are best preserved in the Laramide Denver, Raton, San Juan, Galisteo, and Baca basins.

(3) Middle Cenozoic arid volcanogenic era: From the Late Eocene through the Early Miocene regional igneous activity, including formation of extensive volcanic edifices and caldera complexes as well as broad crustal uplift and erosional rejuvenation of basin fills and uplands spread from northern Mexico northward into Colorado and Utah. Climate pattern developed a strong east-to-west gradient. The southeastern United States remained wet seasonal to subtropical. The west-central Gulf margin and Western Interior assumed a sub-arid to arid climate.

(4) Middle Neogene arid extensional era: The Middle through Late Miocene was characterized by regional north-south extension and creation of major tectonic provinces including the Basin and Range and Rio Grande Rift. Tectonic and/or climatic regime changes triggered erosional unroofing of the long stable Appalachian upland provinces. An arid climate extended across the western Gulf margin and throughout the Western

TABLE 2. PALEOGEOGRAPHIC MAP ELEMENTS	
Regional geomorphic/geologic province outlines	
C/AP	Cumberland/Allegheny Plateau
Rav	Ridge and Valley
BRM	Blue Ridge Mountains
Pmt	Piedmont
OP	Ozark Plateau
OM	Ouachita Mountains
EP	Edwards Plateau
LFTB	Laramide Fold and Thrust Belt
BR	Basin and Range
RGR	Rio Grande Rift
CP	Colorado Plateau
RMOP	Rocky Mountain Orogenic Plateau
MH	Mogollon Highlands
SOB	Sevier Orogenic Belt
Igneous features and provinces	
Active volcanic center	Elevated volcanic edifice with ongoing extrusive activity
Caldera complex	Active upland with explosive volcanism and ash generation
Relict volcanic complex	Potential upland source area
Airborne volcanic ash transport	General atmospheric transport direction
Drainage basin elements	
Mountain glaciers	Area of active upland glaciation
Upland	Elevated region providing both tributary runoff and sediment
High-relief upland	Highly elevated, tectonically active sediment source
Subsiding alluvial basin	Active, long-term repository of alluvial deposits
Bypass alluvial basin	Missing or condensed interval of alluvial deposits
Lacustrine basin	Subsiding basin substantially filled with lake deposits
Eolian basin fill or aggradational erg	Substantial accumulation of wind-born deposits
Aggradational fluvial fan/apron	Geomorphically defined area of alluvial accumulation
Drainage divide	Separating the GOM drainage basin from adjacent drainage basins
Fluvial channel systems	Mapped and inferred tributary, trunk, and distributary river networks
Bed-rock canyons	Local areas of bedrock incised tributary channels
Receiving basin elements	
Depositional coastal plain	Landward and basinward extent of coastal accumulation
Fluvial axes	Principal entry points of extra-basinal river systems
Rio Bravo	RB
Rio Grande	RG
Guadalupe	G
Colorado	C
Houston-Brazos	H-B
Red	R
Mississippi	M
Tennessee	T
Deltaic depocenters	
Maximum progradational shoreline	

TABLE 3. TECTONIC AND PHYSIOGRAPHIC FEATURES LABELED ON FIGURES 4 AND 5

Crustal structural elements	
Rio Grande Rift	
Alamosa basin	AlB
Espanola basin	EB
Albuquerque basin	AbB
Socorro basin	SB
Tularosa basin	TB
Hueco bolson	HB
Laramide basins	
Parras-La Popa	PLP
Sabinas	S
Magiscatzin	M
Tornillo	T
Love Ranch	LR
Carthage-LaJoya	CLJ
Baca	B
Galisteo	G
San Juan	SJ
Raton	R
San Luis	SL
Echo/South Park	ESP
Denver	D
North Park	NP
Piceance	P
Uinta	U
Table Cliffs	TC
Washakie	W
Hannah-Carbon	HC
Green River	GR
Wind River	WR
Big Horn	BH
Powder River	PR
Mountain belts	
Sangre de Cristo Mountains	SdCM
Front Range	FR
Wet Mountains	WM
Uinta Mountains	UM
Wind River Mountains	WRM
Granite Mountains	GM
Big Horn Mountains	BHM
Arches and uplifts	
Sabine uplift	Sbu
Monroe uplift	Mu
Wiggins uplift	Wu
El Burro-Peyotes arches	EBPa
Picachos arch	Pa
Tamaulipas arch	Ta
Rio Grande uplift	RGu
Tularosa uplift	Tu
Sierra Lucero uplift	SrLu
Zuni uplift	Zu
Sandia uplift	Su
Nacamiento uplift	Nu
San Luis uplift	SLu
Defiance uplift	Du
Monument uplift	Mu
Kiabab uplift	Ku
Circle Cliffs uplift	CCu
Casper-Hartsville uplift	CHu
Owl Creek uplift	OCu
San Rafael uplift	SRu
Black Hills uplift	BHu
Igneous features and provinces	
Yellowstone hotspot	Ylh
Ocate-Raton volcanic field	O-Rvf
Springerville volcanic field	Svf
Raton-Clayton volcanic field	R-Cvf
Marysvale volcanic field	Mvf
San Juan volcanic field	SJvf
Central Colorado volcanic field	CCvf
Great Basin volcanic field	GBvf
Mogollon volcanic field	Movf
Trans-Pecos volcanic field	TPvf
Springerville volcanic field	Svf
Sierra Madre Occidental volcanic field	SMOvf
Absaroka volcanic field	Avf

Interior. Middle Cenozoic (late Eocene–Miocene) tributary systems are preserved as aggradational canyon fills and alluvial aprons.

(5) Late Neogene monsoonal epeirogenic uplift era: Return of seasonal monsoonal rainfall across the southern Rockies, climate cooling, and, ultimately, initiation of cyclic montane and continental glaciation rejuvenated erosional evacuation of sediment from the Western Interior. Simultaneously, epeirogenic uplift and tilting along the central and southern Front Range created the east-sloping High Plains. Plio-Pleistocene tributary elements are sparsely preserved in rift basins and local canyon and valley systems.

Interestingly, sediment volume rate of supply is typically quite variable within any one tectono-climatic era. This suggests complex response and significant lag times (millions of years) as continental drainage systems responded to changes in regional controls. Paleogeographic maps illustrate two or three time steps for each era. Below is a discussion of each mapped interval, reviewing (1) the GOM depositional record, (2) the continental tectonic framework, including specific areas of uplift and subsidence, (3) climate pattern, (4) reconstructed drainage basin paleogeography, and (5) source-to-sink relationships.

Late Laramide Era: Early Paleocene

The first three million years of northern Gulf margin history is one of regional marine inundation of the northern basin margin and very low rates of sediment influx (Fig. 1). Shallow shelf deposits extend to outcrop around most of the coastal plain; shoreline position lay inboard of the outcrop (Fig. 7). Positions of fluvial input axes are conjectural. In the Western Interior,

Laramide orogenic activity was approaching the first of two early Cenozoic peaks (Fig. 8). Several uplands were undergoing uplift or were already high standing, including the Front Ranges, Sangre de Cristos, Rio Grande uplift, and Mogollon High.

In contrast to the abbreviated sedimentary record in the Gulf, several large basins of the interior Rockies, notably the Denver, Raton, and San Juan, were actively filling with fluvial sediment during this same time interval (Fig. 8). Early Paleocene basins across eastern Utah, western Colorado, and Wyoming were also subsiding and accumulating fluvial strata. Abundant lignite in the fluvial sequences of all these basins along with vegetation and soil types record widespread distribution of wet temperate to subtropical climate with shallow water tables and voluminous runoff (Flores, 2003). Along the east side of the Front Range, orographic lifting of northwest flowing atmospheric moisture from the Gulf of Mexico created a temperate rain forest (Ellis et al., 2003; Sewall and Sloan, 2006).

The paleogeographic map explains the relative sediment starvation of the Gulf at a time of orogenic elevation of potential source areas. As shown by paleocurrent analyses and preserved trunk stream elements in the adjacent basins, uplands of the northern Rockies drained northeastward into the Cannonball Embayment, an unfilled marine relict of the Cretaceous Interior Seaway (Lillegraven and Ostresh, 1988; Flores, 2003). The drainage divide between the Cannonball and the Gulf extended across southern Colorado (Fig. 7). On the south, uplands of southern New Mexico and Arizona as well as the southeast encroaching Mexican Laramide Fold and Thrust Belt all shed sediment into tributaries that combined to flow southeast into
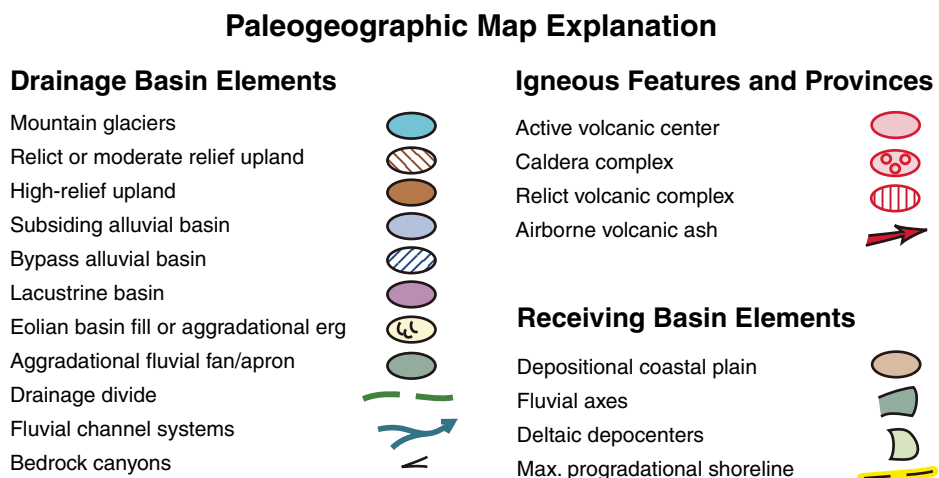
Paleogeographic Map Explanation

Drainage Basin Elements

- Mountain glaciers
- Relict or moderate relief upland
- High-relief upland
- Subsiding alluvial basin
- Bypass alluvial basin
- Lacustrine basin
- Eolian basin fill or aggradational erg
- Aggradational fluvial fan/apron
- Drainage divide
- Fluvial channel systems
- Bedrock canyons

Igneous Features and Provinces

- Active volcanic center
- Caldera complex
- Relict volcanic complex
- Airborne volcanic ash

Receiving Basin Elements

- Depositional coastal plain
- Fluvial axes
- Deltaic depocenters
- Max. progradational shoreline

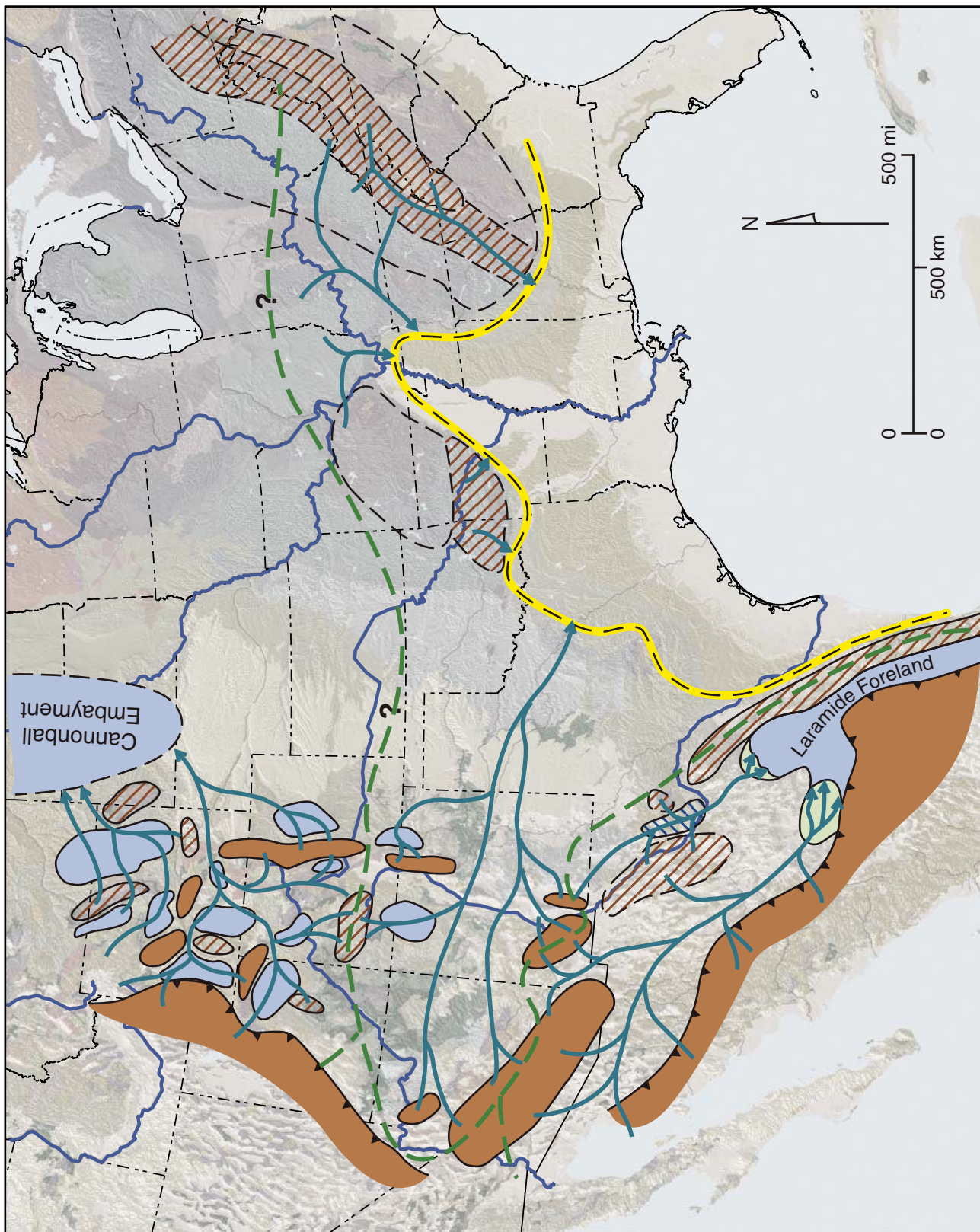**Figure 6. Explanation for symbols used on paleogeographic maps (Figs. 7, 9–14, and 16–19).**

Figure 7. Early Paleocene paleogeography. Compiled from Tweto (1975), Fassett (1985), Smith et al. (1985), Cather (2004), Flores (2003), and Lawton et al. (2009). For explanation see Figure 6.
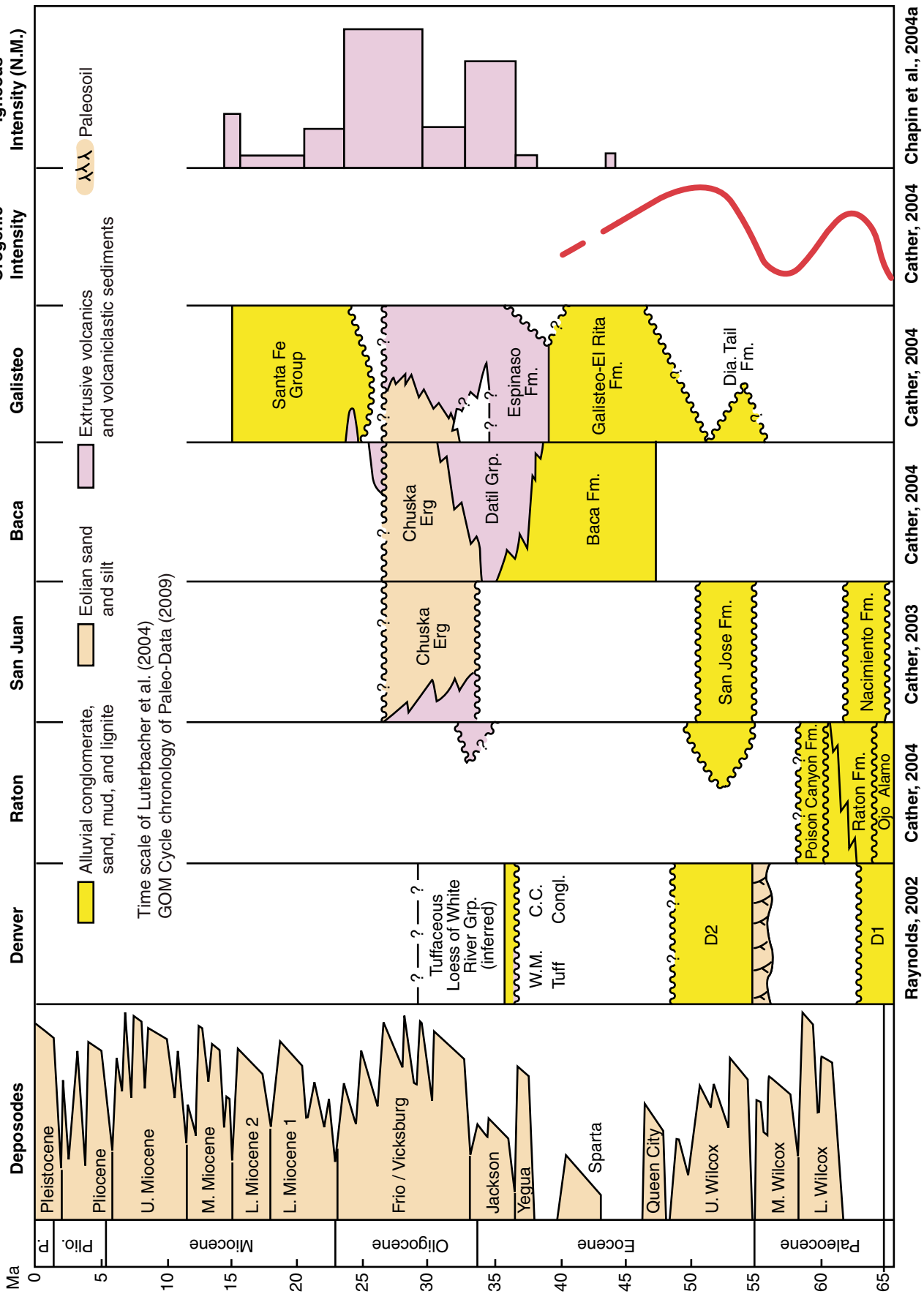
Figure 8. Summary of depositional history in Western Interior basins that lie within drainage basins that empty into the Gulf of Mexico during at least part of the Cenozoic. Left column summarizes the correlative Gulf depositional episodes. The red curve summarizes Laramide orogenic intensity in the Western Interior. Right column summarizes igneous intensity, primarily in New Mexico. Compiled from Raynolds (2002), Cather (2004), and Chapin et al. (2004a, 2004b). Fm.—Formation.

the Sabinas and Parras-La Popa basins at the north end of the narrow, elongate, Laramide foreland basin (Fig. 7). Here the drainage divide extended northwest-southeast along the Mogollon and Rio Grande uplands, east of the Tornillo basin in Big Bend, and along the crest of the forebulge arch of the Mexican foreland basin. Nested between these drainage divides with the north- and south-flowing systems remained only one large drainage basin that extended across New Mexico and Arizona. Tributaries to this fluvial system, sourced by the Sangre de Cristos, flowed south across the San Juan basin and perhaps from the Raton Basin. However, both basins were actively subsiding; resultant fluvial aggradation intercepted and retained sediment otherwise destined for the GOM. Thus the northeastern Gulf record similarly shows that little sediment was derived from remnant Appalachian or Ouachita uplands. The GOM remained relatively sediment starved for the first three million years of the Cenozoic.

Late Laramide Era: Late Paleocene

At the beginning of the Late Paleocene, the shallow marine shelf of the northern GOM was rapidly replaced by a broad fluvial/deltaic coastal plain buttressed by two large fluvially dominated delta systems (Fig. 9). These deltas were centered on the Colorado and Mississippi axes. The continental margin prograded tens of kilometers beyond its inherited Cretaceous position (Galloway et al., 2000). Three principal changes in the western source area triggered the deposition of the lower–middle Wilcox deposodes, a record of one of the great pulses of sediment supply in Gulf Cenozoic history (Table 1B). First, the drainage divide between the Cannonball and Gulf basins migrated northward more than 500 km into southern Wyoming. Second, basins flanking the Front Range and Sangre de Cristo mountains, including the Denver, Raton, San Juan, and associated minor basins, entered a Late Paleocene phase of limited fluvial accumulation, bypass, and/or extensive pedogenesis (Fig. 8). Sediment from adjacent uplands previously sequestered in these basins now continued on through the trunk streams to the northern GOM. Third, integration of the Western Interior drainage network established two large rivers, one draining southeast to the Colorado axis and the second flowing eastward across the Midcontinent lowland before turning south into the Mississippi Embayment. The northerly system, stretching more than 1500 km across the continental interior (Fig. 9), at first seems unlikely. However, the large size of Mississippi axis delta demands a large drainage basin with actively eroding uplands. Absence of significant Paleo-

cene clastic sediment along the Atlantic margin (Poag and Sevon, 1989) makes the eastern U.S. uplands unlikely sources. Further, the abundant presence of volcanogenic rock fragments in the Wilcox of Louisiana (Dutton, 2010, personal commun.) necessitates an exposed volcanic source. The Colorado Mineral Belt provides the only volumetrically significant candidate.

Late Paleocene paleoclimate patterns continued to reflect strongly monsoonal conditions, with moisture drawn from the GOM (Sewall and Sloan, 2006). Orographic lift of moisture-laden air perpetuated the narrow belt of tropical rainforest along the east flank of the Front Range and Sangre de Cristos (Ellis et al., 2003). Warm subtropical to subarid, seasonal climates extended west and southwest across western Colorado, New Mexico, and Arizona. Abundance of seasonal runoff nourished large trunk channels. This is, in turn, reflected in the very large dimensions of Wilcox meander belts seen in outcrop and the shallow subsurface and in the large deltas they constructed. Southeastern U.S. and Gulf coast paleoclimate was tropical monsoonal; the Paleocene Wilcox Group contains extensive, commercial lignite deposits in fluvial, deltaic, and shore-zone depositional systems.

Early Paleocene uplands remained high-standing. Closed, interior drainage networks developed to the east of the Sevier Orogenic Belt in western Wyoming, Utah, and northwestern Arizona (Fig. 9). However, the Green River basin gathered headwaters into an east-flowing trunk that drained between the north end of the Front Range and the Casper-Hartsville uplift. In contrast to the Early Paleocene, when this system flowed northeast into the southern end of the Cannonball seaway, it was now destined for the Mississippi fluvial/deltaic axis. The Colorado Mineral Belt sourced volcanic rock fragments that are a significant component of both Colorado and Mississippi system sandstones. Their presence in the Wilcox fluvial axes of the GOM coastal plain (Dutton, 2010, personal commun.) confirms that the fluvial systems had tributaries extending into central Colorado. Detrital zircon U-Pb data document Southern Rockies Laramide crystalline block, Cordilleran arc, and northern Mexico sources for sediment transported by tributaries of the Colorado system (Hutto et al., 2009; Mackey, 2009). To the south, fluvial systems derived from the southern flanks of the Mogollon and Rio Grande and from the Laramide uplands sourced fluvial deltaic systems in the northern end of the narrow foreland basin. Little sediment was supplied by the remnant Appalachian uplands to either the Gulf or to the Atlantic (Poag and Sevon, 1989).

Terminal Laramide Era: Early Eocene

Onset of Eocene deposition in the GOM is recorded by the Upper Wilcox deposode (Fig. 1). Paleogeography of the northern basin margin displays several major fluvial/deltaic systems. The principal fluvial/deltaic axis shifted significantly southward along the Texas coastal plain. Paleocurrent data and mapped paleochannel trends (Hamlin, 1988) show that the very large extrabasinal river feeding this delta entered the paleocoastal plain from the north at the same position as the Late Paleocene Colorado axis; it thus retains the Colorado name. Occupying the northeast part of the Paleocene Colorado location on the paleocoastal plain are deposits of a new fluvial/deltaic axis, the Houston-Brazos. Though the trunk fluvial axes are closely spaced, differences in bulk sandstone composition (Loucks et al., 1986) show them to have different sources and thus to record two contemporaneous drainage systems. A third delta occupies the Rio Grande axis on the south Texas paleocoastal plain. It too is compositionally distinct. A small deltaic depocenter records the continued presence of the Mississippi axis. However, this system was in decline; channel elements were small and the Upper Wilcox records long-term transgression of the east-central Gulf margin. A very small delta complex in southern Mississippi is the only depositional evidence for the presence of a drainage basin extending into the Appalachian uplands.

A second late Laramide tectonic pulse (Fig. 8) significantly affected the landscape of the Western Interior (Fig. 10). In addition to continued presence of the Front Range, Sangre de Cristo, Rio Grande, and Mogollon uplands, numerous mountain ranges of Wyoming were uplifted and the series of arches and uplifts extending from southeastern Utah to south-central New Mexico were elevated. Additional positive elements, including the San Luis and Nacimiento uplifts, expanded upland source areas along the southern Rockies. Far-field tectonic adjustments of the intracontinental crust are reflected in the rejuvenation of the Sabine and Monroe uplifts in the central Gulf margin. At the same time, rejuvenated subsidence triggered or accelerated accumulation of at least some fluvial or lacustrine deposits in all of the basins adjacent to the active mountain belts (Fig. 10).

Early Eocene climate indicators and modeling suggest drier conditions across the Western Interior and Gulf Coast relative to the Paleocene (Wilf, 2000; Davis et al., 2009). Warm temperate climate of the Gulf margin graded to warm subarid along the Rockies. Peat accumulation, characteristic of Paleocene deposits from the Wyoming basins to the Gulf Coast, ceased.
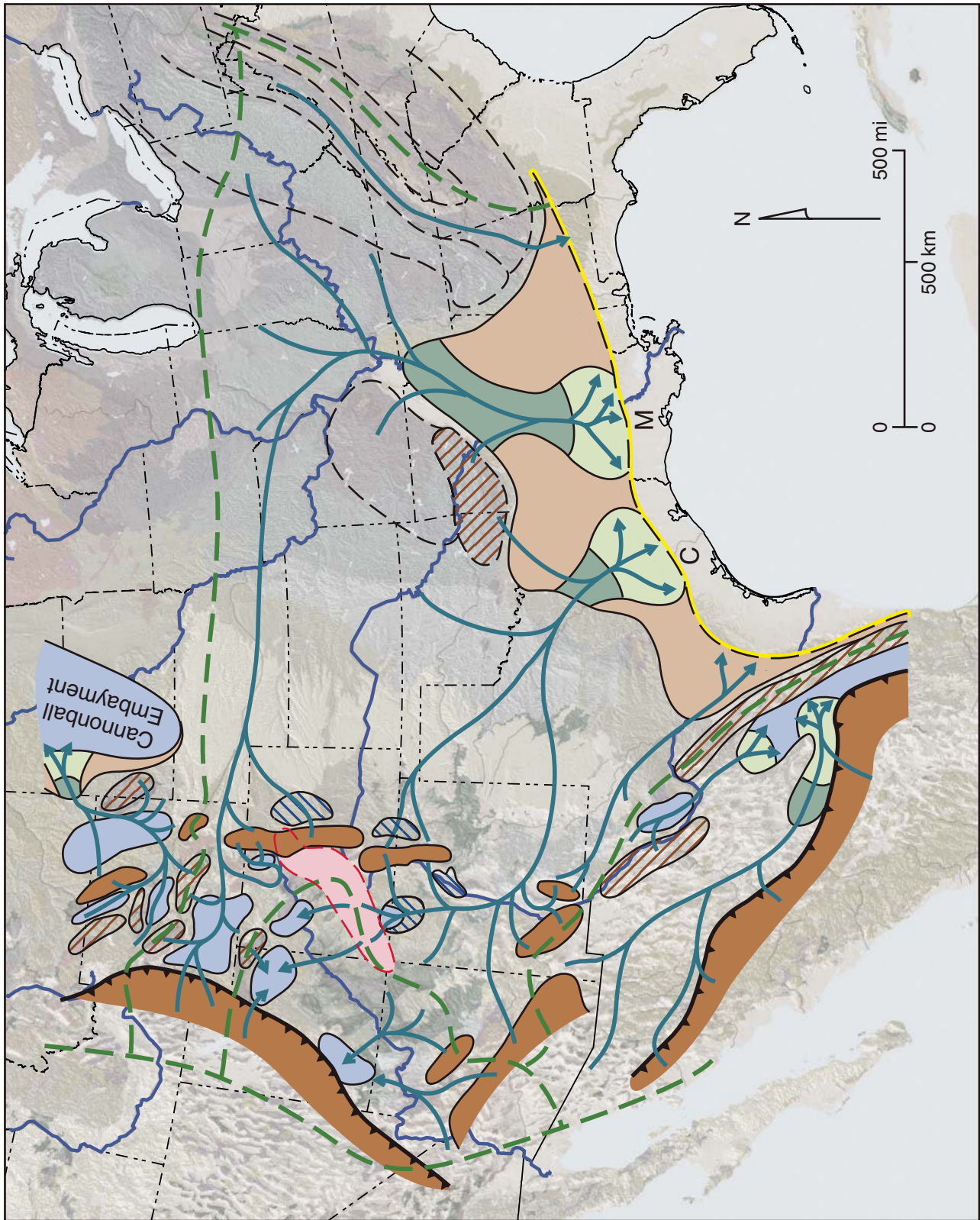
Figure 9. Late Paleocene paleogeography. Compiled from Fassett (1985), Smith et al. (1985), Dickinson et al. (1988), Lillegraven and Ostresh (1988), Cather and Chapin (1990), Lehman (1991), Pazzaglia and Kelley (1998), Cather (2004), Flores (2003), Milner et al. (2005), Flowers et al. (2008), and Lawton (2008). For explanation see Figure 6.
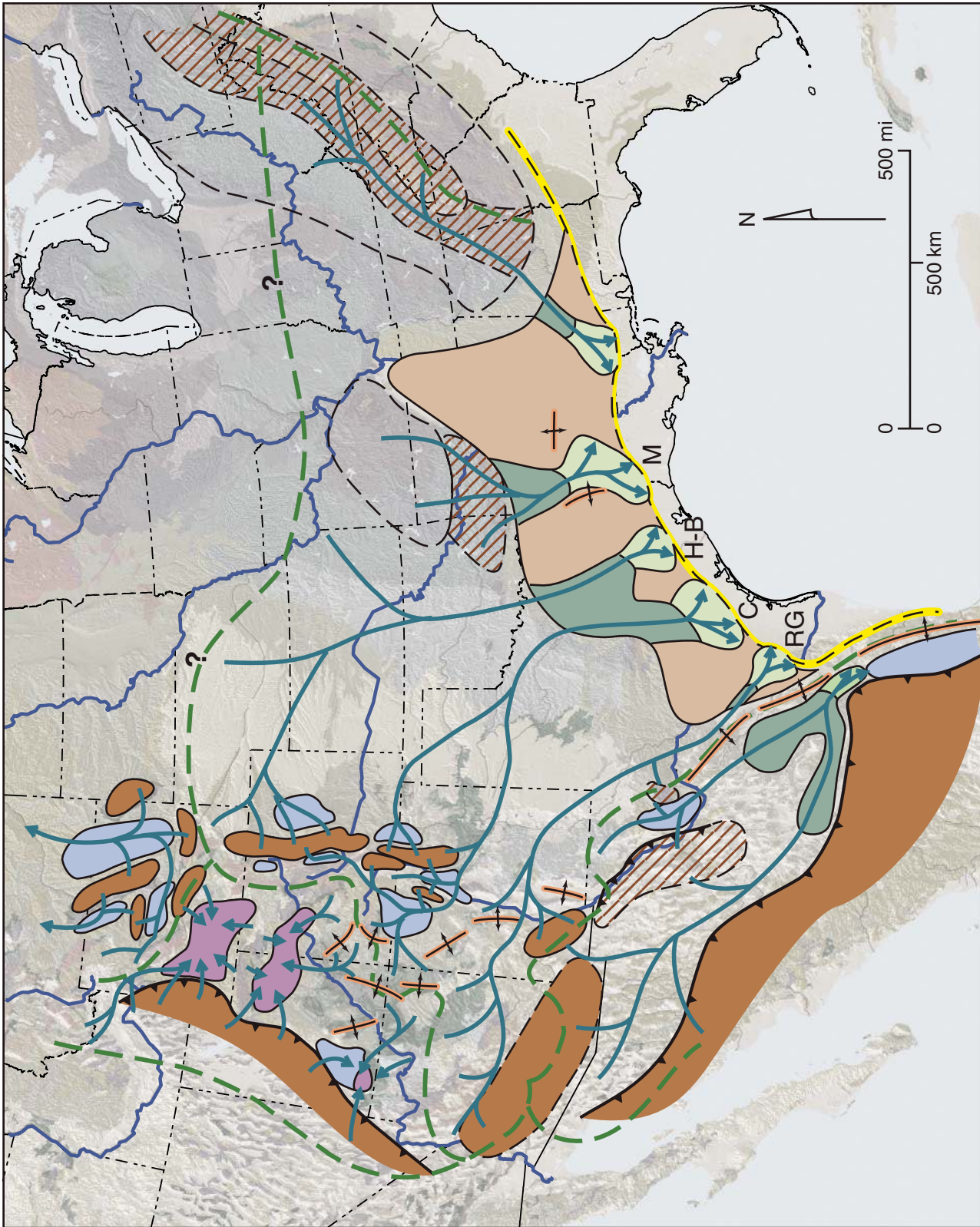
Figure 10. Early Eocene paleogeography. Compiled from Fassett (1985), Smith (1992), Dickinson et al. (1988), Lillegraven and Ostresh (1988), Cather and Chapin (1990), Lehman (1991), Seager et al. (1997), Pazzaglia and Kelley (1998), Holm (2001), Cather (2004), Flores (2003), Milner et al. (2005), Flowers et al. (2008), Lawton (2008), Smith et al. (2008), and Davis et al. (2009). For explanation see Figure 6.

However, sufficient runoff existed to create large trunk streams that ultimately entered the GOM as the Rio Grande, Colorado, and Houston-Brazos axes.

Tectonic reorganization of the Western Interior and its more subtle influences within the adjacent intracontinental lowland resulted in significant reorganization of fluvial drainage systems. The tributary system extending from central Arizona across southern New Mexico was diverted southward, greatly expanding the headwaters of the previously insignificant Paleocene trunk stream (Fig. 9). This newly integrated and expanded river system transported sufficient load to initiate the Upper Wilcox Rio Grande fluvial/deltaic depocenter. The drainage divide separating this system from a comparably large system that drained into the northern end of the Laramide foreland basin was little changed from its Paleocene position. Uplands in Mexico were effectively separated from drainage elements lying in the southwestern United States, and their sediments were diverted into a foreland trough that was equally separated from the GOM basin by a continuous fore-bulge (Fig. 10). A tributary network with preserved elements in the Echo/South Park, San Juan, Galisteo, and Raton basins (Fig. 8) converged eastward to source the Colorado axis (Fig. 10). Somewhere in north central Texas, this trunk stream turned southward to enter the Gulf paleocoastal plain obliquely from the north. The eastern Front Range was the principal source for tributaries preserved in the Denver basin as the D2 sequence (Fig. 8). The extensive east-flowing trunk stream that had connected to the Paleocene Mississippi axis (Fig. 9) was diverted to or captured by the Houston-Brazos system, and provided the principal sediment supply to that system. This diversion is reflected in the decline in sediment supply through the Mississippi axis combined with the appearance of the new fluvial/deltaic depocenter along the upper Texas paleocoastal plain. By the end of Early Eocene Wilcox deposition, the emergent Sabine uplift and remnant Ouachita uplands appear to have provided local quartz-rich sediment sources for the remnant Mississippi drainage system (Dutton, 2010, personal commun.).

A drainage divide separated western headwaters of the Colorado and Houston-Brazos drainage basins from an extensive system of closed interior basins that includes the fluvio-lacustrine greater Green River, Uinta, and Table Cliffs basins (Fig. 10). Uplands of central and northern Wyoming drained northward toward Canada (Lillegraven and Ostresh, 1988).

Tectonically rejuvenated and expanded uplands provided an ample source of sediment that could potentially have been transported to the northern GOM. Indeed, sediment supply was appreciable. However, the grain volume rate of supply was on the order of five times lower than that of the Late Paleocene Lower Wilcox peak (Fig. 1). There are several reasons for this decline in the face of the plethora of potential sources. (1) Supply from the Wyoming Rockies and from the southern Laramide foreland continued to be captured by drainage basins that did not discharge into the Gulf. (2) The area of closed, interior drainage expanded, removing the Greater Green River basin and its surrounding uplands from Gulf-bound rivers. (3) Much sediment derived from the Front Range and associated uplifts was sequestered in the family of subsiding basins that flanked them. The significant changes in drainage patterns—appearance of a distinct Rio Grande axis, southward shift of the Colorado axis, and diversion of former Mississippi axis headwaters to initiate the Houston-Brazos axis—suggest that changing intraplate stress patterns caused by the final Laramide pulse effected broad, low-relief adjustments in the continental platform that, in turn, realigned trunk channel pathways connecting the Western Interior sources with Gulf paleocoastal plain depocenters.

Terminal Laramide Era: Middle Eocene

The Middle Eocene was an extended period of tectonic quiescence at the end of the Laramide era in the continental United States. This period was recorded in the northern GOM by two minor deposodes, the Queen City and Sparta, contained within a 10 Ma interval of very low sediment accumulation and extensive marine inundation (Fig. 1). Both deposodes have three small fluvial/deltaic depocenters in common: the Rio Bravo, the Rio Grande, and the Houston-Brazos (Fig. 11). Initially, the Mississippi embayment was a broad marine bay with no evidence of significant fluvial supply during the Queen City deposode. Later, a modest Mississippi fluvial/deltaic system reclaimed the east-central Gulf margin from the sea during the Sparta deposode. The Rio Bravo axis records sediment supply from northern Mexico uplands that entered the GOM following filling of the Parras-La Popa and Sabinas basins and overflow through a saddle in the forebulge. Once formed, this fluvial axis remained distinct from the Rio Grande axis for much of Cenozoic time (Fig. 3).

Residual Laramide uplands and basins largely defined the Western Interior physiography of the Middle Eocene (Fig. 11). Principle basins of the northern Rockies remained little changed in outline, but many were largely filled and accommodated little additional sediment. In contrast, a family of new basins, mostly small in area, developed across western New Mexico. The largest of these, the Baca basin, extended westward into Arizona (Fig. 11). The Baca and Galisteo basins accumulated thick successions of Middle Eocene fluvial sediment (Cather and Johnson, 1984) (Fig. 8). Basins surrounding the central Rockies filled and merged into a broad, low-relief aggradational alluvial apron that onlapped the uplands. At the same time, several million years of weathering and erosion subdued the topography of the highlands, creating a combined depositional and erosional surface that extended along the Front Range southward into northern New Mexico. This surface truncated older Cenozoic strata, beveled crystalline Precambrian cores, and extended eastward onto the Great Plains (Epis and Chapin, 1975).

Climate across the paleocoastal plain was subtropical. Gulf moisture spread inland, creating warm temperate to subtropical conditions along the eastern Rockies (Sewall and Sloan, 2006). Warm temperate to subarid regimes characterized the Western Interior, as reflected in paleosoils and shallow lake deposits (Davis et al., 2009).

Preserved tributary segments in the New Mexico basins and depocenter volumetrics suggest some modification in patterns of tributary integration into the trunk streams. The Rio Grande drainage basin is best documented by paleocurrent, compositional, and sand body trends in the Baca, Galisteo, Carthage-La Joya, and Love Ranch basins. North-to-south transport along the Galisteo-Carthage-La Joya axis indicates that drainage from the northern New Mexico uplands was displaced southward to join with the Baca basin overflow as principal sources of the Rio Grande axis. The Greater Green River basin filled with sediment and fluvial tributaries collected there to flow south around the east end of the Uinta Mountains into the lacustrine Uinta basin (Fig. 11). To the south, the Table Cliffs basin collected streams draining northern Arizona. Thus, the continental divide extended along the Front Range and Wet Mountains, jumped westward to the Monument uplift, and then ran diagonally southwest across Arizona. To the east, reappearance of a Mississippi axis fluvial/deltaic system suggests reintegration and expansion of the Midcontinent drainage basin. Appalachian uplands provided no significant fluvial sediment supply to the northern Gulf margin or to the Atlantic.

Sediment supply to the Gulf was derived primarily from the eastern slopes of the Front Range, the local uplands of New Mexico, and Laramide uplands of northern Mexico (Fig. 11). The rate of sediment reaching the Gulf was further reduced from the already low Early Eocene
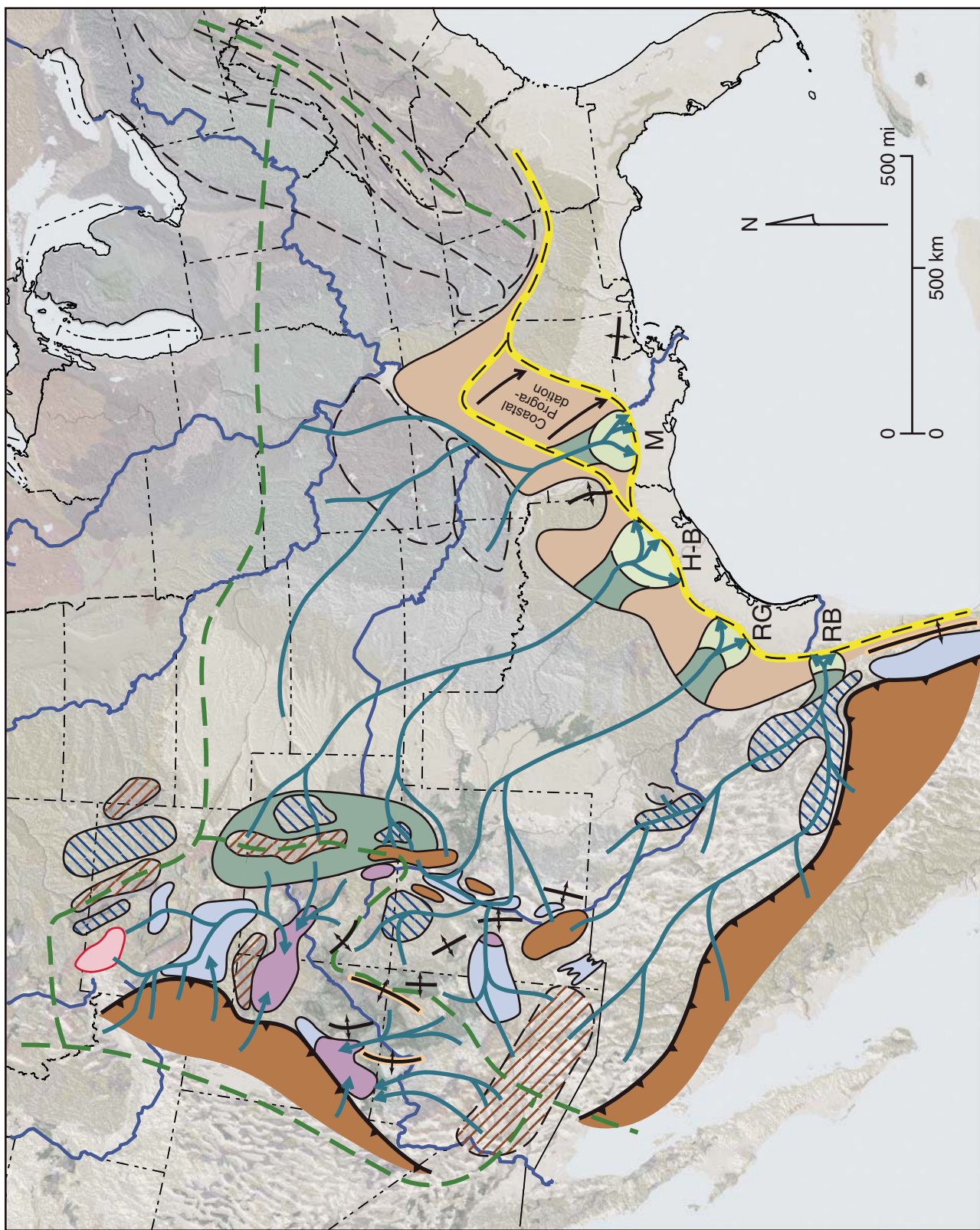
Figure 11. Middle Eocene paleogeography. Compiled from Scott (1975), Cather and Johnson (1984), Lehman (1991), Lozinsky (1994), Seager et al. (1997), Dickinson et al. (1988), Pazzaglia and Kelley (1998), Cather (2004), Smith et al. (1985, 2008), Lawton (2008), Davis et al. (2009), and Lawton et al. (2009). For explanation see Figure 6.

values by several factors. (1) The area of closed interior drainage expanded to the west slope of the Front Range and southward across Arizona. (2) Much of the sediment eroded from the Front Range, Wet Mountains, and Sangre de Cristo mountains accumulated in the aggrading apron around these uplands, reducing supply to the Houston-Brazos system. (3) The Baca, Galisteo, and additional small basins trapped and retained a significant proportion of sediment eroded from headwater sources of the Rio Grande system. (4) Although its drainage basin grew, relief and, consequently, sediment yield to the Mississippi system remained low. Only the Rio Bravo drainage basin was positioned to collect and transport sediment from tectonic uplands of the Laramide foreland; it emerges as the principal Middle Eocene depocenter of the northern Gulf margin (Galloway et al., 2000).

Middle Cenozoic Arid Volcanogenic Era: Late Eocene

The continental landscape was dramatically altered by a series of middle–late Cenozoic tectonic and climatic events (Fig. 5). Laramide basins and uplands were modified, overprinted, and occasionally rejuvenated by successive regional thermal, extensional, and climate-induced processes. A variety of new landscapes, including local and regional uplifts, volcanic edifices, subsiding basins, and aggradational alluvial and eolian depositional systems, effected sediment yield and drainage patterns. The first of these new eras, the middle Cenozoic arid volcanogenic era, was defined by regional crustal heating, with associated uplift, volcanism, and widespread air-fall ash dispersal, and increasing aridity across the Western Interior, all superimposed on the remaining vestiges of Laramide basins and uplifts.

Following the mid Eocene era of extremely low sediment supply to the GOM basin, late Eocene deposition displayed an abrupt 1–2 Ma spike (Fig. 1). The high Yegua supply rate rapidly moderated during the latest Eocene Jackson deposode. Three fluvial/deltaic axes, the Rio Bravo, Rio Grande, and Houston-Brazos, occur in both deposodes; disappearance of the Mississippi axis and regional coastal retreat in the central and eastern Gulf margin accompanied decreased accumulation rate in the Jackson deposode (Fig. 12).

In the western interior, most of the Laramide Mountains remained elevated. Interior closed basins, including the greater Green River, Uinta, Piceance, and Table Cliffs filled with alluvial or fluvio-lacustrine deposits (Fig. 12). Prominent Laramide basins, including the Denver, Raton, and San Juan, largely bypassed alluvial

sediment, with only thin, local, or intermittent accumulation (Fig. 8). In contrast, southern, late Laramide basins, notably the Baca, Galisteo, Love Ranch, and Carthage La Joya, continued to accumulate substantial alluvial and volcaniclastic successions. The most important change in sediment source areas was the emergence of several large igneous complexes, including the Trans-Pecos, Sierra Madre Occidental, Mogollon, San Juan, and Great Basin volcanic fields (Fig. 12). The first of two great peaks in igneous intensity across the southwestern United States culminated in the late Eocene to early Oligocene (Chapin et al., 2004a, 2004b) (Fig. 8). Source areas were rejuvenated in several ways. (1) Regional heating was accompanied by crustal uplift. This triggered rapid erosion of the shallow, unconsolidated mid Eocene basin fill and apron surrounding the Front Range. Renewed incision of canyons into and through the mountain crystalline bedrock cores followed. Among others, the ancestral Platt and Arkansas River canyons were cut. (2) The extrusive igneous complexes constructed formidable uplands composed of flows and erodible volcaniclastics. (3) Explosive volcanism and accompanying caldera formation spewed large volumes of ash into the upper atmosphere. This ash was transported northeastward across the continental interior by upper atmospheric winds.

A subtropical climate persisted across the northern Gulf coastal plain; lignite is abundant in both Yegua and Jackson delta and shore-zone strata. The interior lowlands and Appalachians remained warm to cool temperate. The Western Interior, in contrast, was increasingly dominated by arid to subarid conditions.

Four Gulf-directed drainage basins evolved on this dynamic landscape (Fig. 12). In the northwest Gulf margin, the Rio Bravo collected tributary systems arising in the Sierra Madre Oriental and Trans-Pecos volcanic fields. This system drained, in part into the Gulf, but may have intermittently remained trapped as a longitudinally flowing river within the now in-filled Mexican foreland trough. The Rio Grande axis collected sediment through an extensive tributary network that extended from the northeast flanks of the Trans-Pecos and Sierra Madre Oriental volcanic fields across the Baca basin and local central New Mexico basins, to remnant sags in the Four Corners areas and San Juan basin. Volcaniclastic sediments increasingly dominated the fill of these basins (Fig. 8). As expected, abundance of feldspar and volcanic rock fragments in Yegua and Jackson sandstones of South Texas attest to the importance of volcanic source areas for the Rio Grande system. The presence of lesser but significant percentages of volcanic grains and ash in

sandstones of the Houston-Brazos axis reflects its headwaters in the Front Range and through canyons that extended to eastern elements of the San Juan volcanic field. The Mississippi fluvial/deltaic depocenter, which was well nourished in the Yegua deposode, disappeared in the latest Eocene as increasing aridity in the northern Rockies triggered aggradation of the extensive White River alluvial/eolian apron. Sediment storage in the apron, beginning ca. 37 Ma, resulted in downstream starvation and consequent transgression of the northern Gulf delta system during the contemporaneous Jackson deposode. As before, no appreciable sediment was derived from the relict Appalachians.

In summary, the late Eocene history was one of thermally driven uplift and consequent erosional exhumation of old mountain belts, combined with evacuation of the mid Eocene sediment apron, erosion of newly forming volcanic uplands, and recycling of air-fall ash into fluvial systems. However, the initial surge of sediment supply was soon tempered as spreading volcanic fields disrupted and blocked tributary systems of New Mexico and northeastern Arizona and as increasing aridity limited erosion and runoff. At the extreme, fluvial outflow from the northern Rockies was unable to remove available sediment, leading to aggradation of the White River apron and consequent death of the Mississippi axis.

Middle Cenozoic Arid Volcanogenic Era: Oligocene

The Oligocene Frio/Vicksburg deposode is one of the longest and volumetrically most important in GOM history (Fig. 1). Four major fluvial/deltaic axes persisted for more than 10 Ma, bringing, on average, more than 50,000 km³ of sediment into the Gulf each million years. The largest fluvial input axis was the Rio Grande, followed by the Mississippi, Houston-Brazos, and Rio Bravo (Fig. 3). Each axis is distinguished by sand compositional attributes that further specify likely drainage basin sources (Galloway, 1977; Loucks et al., 1986).

The second great peak of volcanism in the southwestern interior occurred in the middle to late Oligocene (Chapin et al., 2004a) (Fig. 8). The volcanic uplands established in the late Eocene, including the Sierra Madre Occidental, Mogollon, Trans-Pecos, San Juan, and Basin and Range, grew in volume and area. Numerous peripheral and outlier volcanic fields, such as the Marysvale and Springerville, further expanded the footprint of volcanic uplands (Fig. 13). Widespread caldera complexes continued to pour immense volumes of volcanic ash into the upper atmosphere, where the prevailing
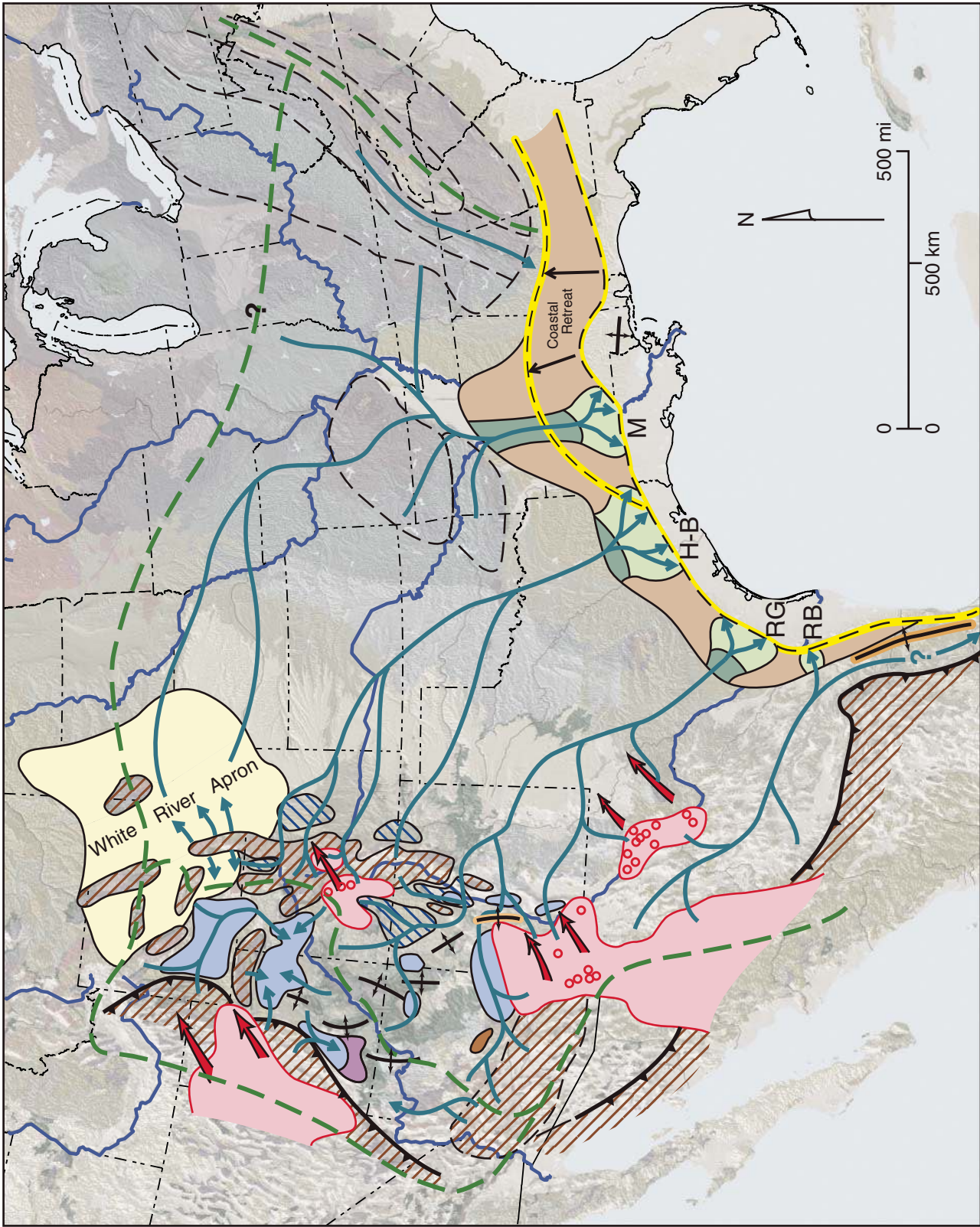
Figure 12. Late Eocene paleogeography. Compiled from Epis and Chapin (1975), Evanoff (1990), Lillegraven and Ostresh (1988), Lozinsky (1994), Bolroyd (1997), Steven et al. (1997), Larsen and Evanoff (1998), Holm (2001), Cather (2004), Chapin et al. (2004a, 2004b), McMillan et al. (2006), Cather et al. (2008), Flowers et al. (2008), Lawton (2008), and Davis et al. (2009). For explanation see Figure 6.
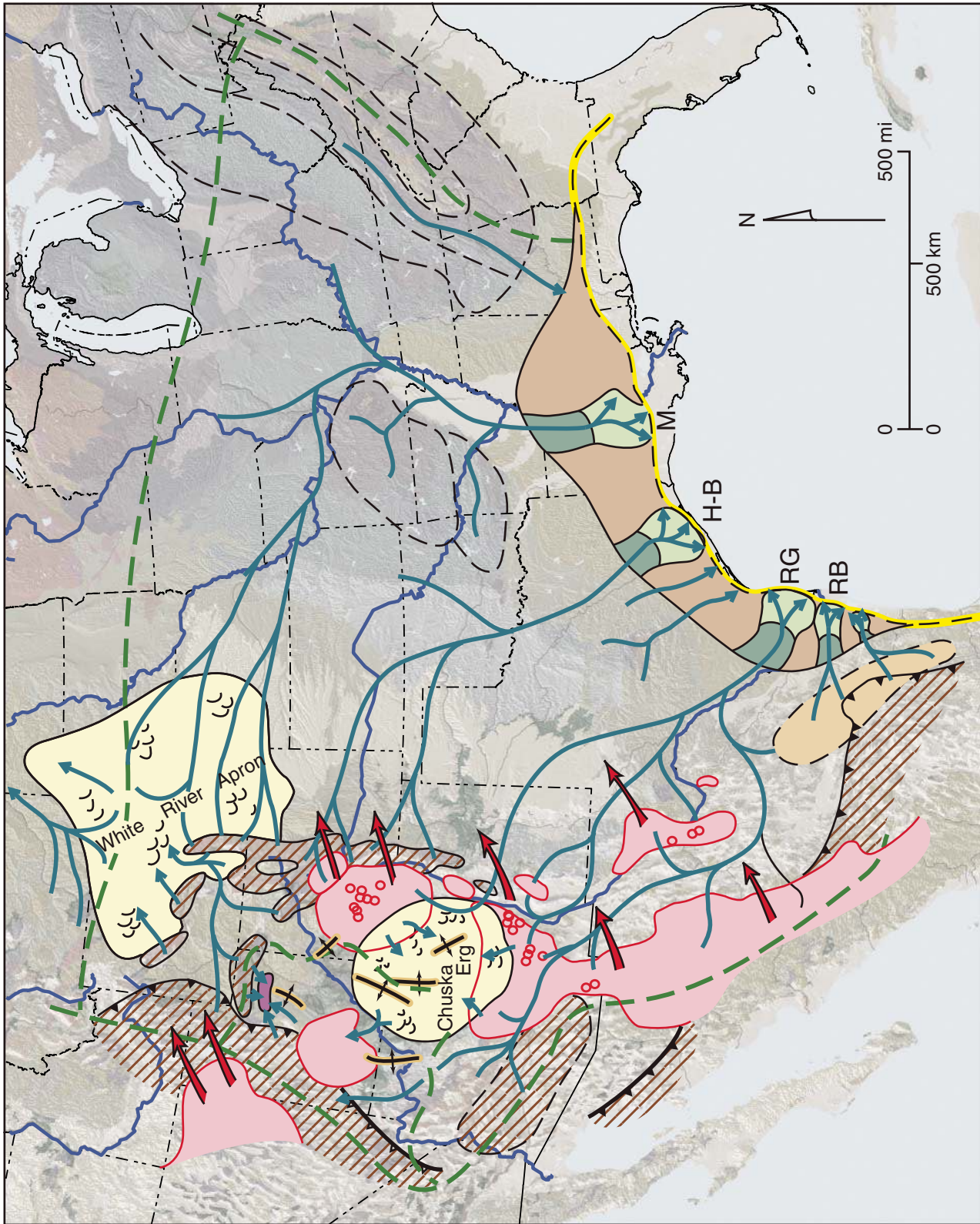
Figure 13. Oligocene paleogeography. Compiled from Clark (1975), Epis and Chapin (1975), Scott (1982), Evanoff (1990), Lillegraven and Ostresh (1988), Ferrari et al. (1999), Steven et al. (1997), Larsen and Evanoff (1998), Pazzaglia and Kelley (1998), Holm (2001), Chapin et al. (2004a, 2004b), McMillan et al. (2006), and Cather et al. (2008). For explanation see Figure 6.

circulation dispersed it eastward across the continental interior. Although the major Laramide-created mountain belts remained as uplands, all topographic reflection of Laramide basins disappeared. Subregional inversion and erosion of the Laramide foreland basin in northeastern Mexico disrupted the regional drainage pattern, but provided a local source for the Rio Bravo and smaller streams draining into the adjacent Gulf.

By the beginning of the Oligocene, the North American continent had established the strong east-to-west climate pattern seen today (Galloway, 2008). A subtropical eastern Gulf margin transitioned across East Texas to a subarid south Texas. The temperate eastern Mid Continent graded into a subarid climate along the eastern Front Range, which gave way, in turn, to a hot arid (south) to cool arid (north) Western Interior. Dry climate, abundant volcanic ash, and strong west-to-east winds created the extensive Chuska erg across the Colorado Plateau, nested between the Springerville, San Juan, and Marysvale volcanic fields (Cather et al., 2008) (Figs. 8 and 13). In the northern Rockies, the White River apron continued to aggrade by accumulation of ephemeral stream and eolian deposits. Limited runoff or fluvial-borne sediment escaped these large, intracontinental depositional complexes.

Continued presence of three large fluvial/deltaic depocenters (Galloway et al., 2000; Galloway, 2008), as seen in the late Eocene deposodes (Fig. 12), records three comparable continental drainage basins (Fig. 13). Sands of the Rio Grande axis, characterized by their abundant volcanic rock fragments and feldspars (Galloway, 1977; Loucks et al., 1986), reflect the dominance of the Trans-Pecos, southern New Mexico, and northern Mexico volcanic centers. The presence of volcanic lithic fragments but increased proportion of quartz and feldspar in sands of the Houston-Brazos axis reflect a mixed source; tributaries are shown tapping the central Rockies, including the east flanks of the San Juan and Central Colorado volcanic fields (Fig. 13). Although the continental drainage divide is placed along the Utah/Colorado and northern Arizona/New Mexico lines, it is likely little sediment derived from the west flanks of the Rockies or of the San Juan, Springerville, or Mogollon volcanic fields ultimately reached the GOM. It would more likely have remained trapped as stream flow dissipated by evaporation and infiltration into the Chuska erg and White River apron.

Further east, sands of the Mississippi axis are quartz rich and lack evidence of direct volcanic input. The paleogeographic reconstruction shows an extensive network of east-flowing tributaries draining the east side of the northern Rockies and collecting limited outflow from the distal White River apron (Fig. 13). This system displays the largest drainage basin, but transported the least amount of sediment directly from upland sources. It did, however, collect reworked air fall volcanic ash and its argillaceous alteration products from an extensive area of the northern and central Mid Continent. These same tributaries would also have benefitted from runoff from the wet climate regimes of the eastern United States. Together this reconstruction explains why the Mississippi system depocenter, though large in volume, is mud rich in comparison to its sand-rich contemporaries in Texas and northern Mexico (Galloway et al., 2000).

To the south, quartzite cobbles found in the outcropping Norma Conglomerate, the core fluvial facies of the Rio Bravo axis, suggest basin-margin sourcing from the adjacent inversion uplift. This uplift likely deflected the late Eocene tributary systems that drained northern Mexico (Fig. 12) into the Rio Grande trunk system (Fig. 13), further augmenting its volumetric importance.

In summary, two competing controls determined long-term Oligocene sediment yield and transport to the GOM basin. Regional thermally driven uplift, construction of volcanic edifices, and dispersal of easily eroded volcanic ash all combined to enhance sediment yield to Oligocene drainage basins. At the same time, however, increasing aridity across the Western Interior limited the availability of runoff to remove that sediment to trunk streams and thence to the GOM. Wind played an increased role in transport and deposition. As a result much sediment was sequestered near the source uplands as vertically aggraded fluvial and eolian depositional systems. Notably, and in contrast to the Laramide era that came before, basin subsidence did not provide significant sediment traps. The result was an extended history of moderate accumulation in the GOM (Fig. 1) with textural and compositional gradients reflecting the specific interplay of area, source terrain composition and elevation, and paleoclimate of each drainage basin.

Middle Cenozoic Arid Volcanogenic Era: Early Miocene

Volume rate of sediment supply to the GOM initially decreased in the Early Miocene (LM 1, Fig. 1 and Table 1A). However, in late Early Miocene (LM 2, Fig. 1 and Table 1A) it again accelerated, presaging the high rates of the Middle–Late Miocene. Distribution of lower Miocene fluvial/deltaic depocenter distribution and relative volumes presages the major shift of sediment supply from the northwestern to the east-central GOM that defines the Neogene. Rio Bravo and Rio Grande axes remained prominent features of the early Miocene paleogeography (Fig. 14). The Houston-Brazos axis shifted to a position astraddle the Texas-Louisiana state line. This shift, together with the interpreted change in drainage basin configuration, suggests recognition of this axis as a new system, the ancestral Red River. The Mississippi axis persisted in its central Louisiana location and increased in relative volumetric importance. By late Early Miocene, it was the dominant depocenter (Galloway et al., 2000).

Early Miocene was a time of transition in the Western Interior of North America. Volcanic activity waned (Fig. 8); only the Trans-Pecos and Marysvale volcanic fields remained active (Fig. 14). Caldera formation ceased. However, extensive relict volcanic uplands extended from southwestern Colorado into northern Mexico. Basin and Range extension became the dominant theme of western North American tectonics. Block faulting creating aligned uplands and adjacent narrow, subsiding basins extended from western Utah, across western Arizona, and diagonally into central Mexico. Basin and Range uplands extended across the modern Rio Grande into Trans-Pecos Texas and southern New Mexico, where local fill accumulated in grabens (Fig. 15). In addition, early extension along the north-trending Rio Grande Rift initiated several small basins in central New Mexico (Fig. 14) where local volcanics and terrestrial sediments collected (Fig. 15). Initial rift shoulder uplift rejuvenated the southern Rockies. Between the Basin and Range and the Rio Grande Rift, the nearly circular, stable Colorado Plateau occupied the Four Corners and surrounding area. The Chuska erg, which had began to be reworked by the late Oligocene, was eroded. At the northern end of the Rockies, a mixed alluvial and eolian apron, recorded first by the Arikaree Group and then by broad valley fills of the northern Ogallala Group accumulated across eastern Wyoming and adjacent states (Fig. 16). The Edwards Plateau of central Texas was elevated, providing a compositionally distinct (early Cretaceous limestone) basin-margin source. The elevation of the plateau, though modest, likely deflected the Houston-Brazos trunk stream northward and eastward to a position more like that of the modern Red River. In summary, only a few, small, moderately subsiding rift basin segments provided sediment sinks among or marginal to the Western Interior uplands. Elsewhere, Early Miocene units are thin or occupy topographic lows in a generally degradational landscape.

The pattern of continental aridity established in the Oligocene persisted through the Early Miocene (Cather et al., 2008; Chapin, 2008). All of the Western Interior was arid; arid conditions extended to the Northwest Gulf margin
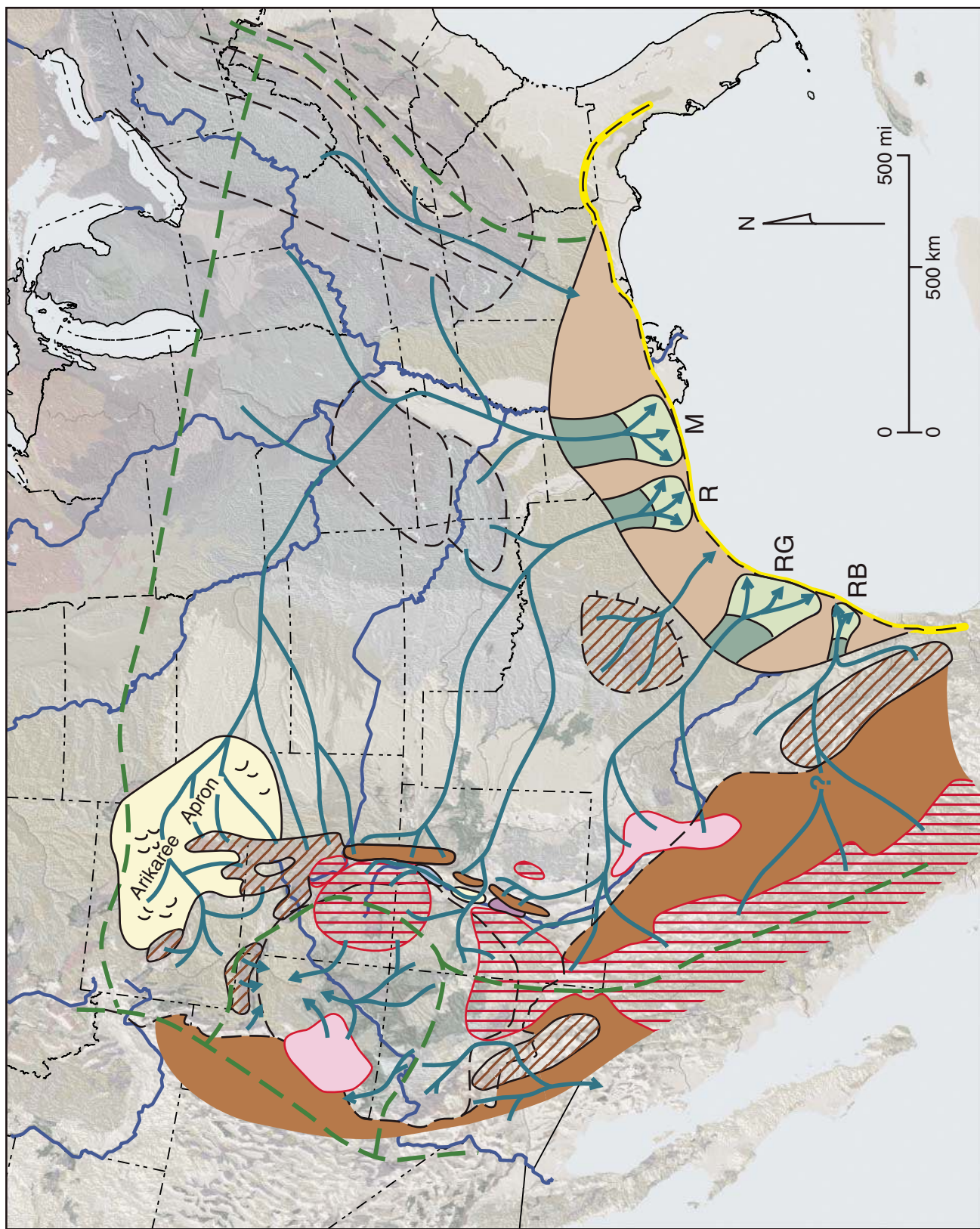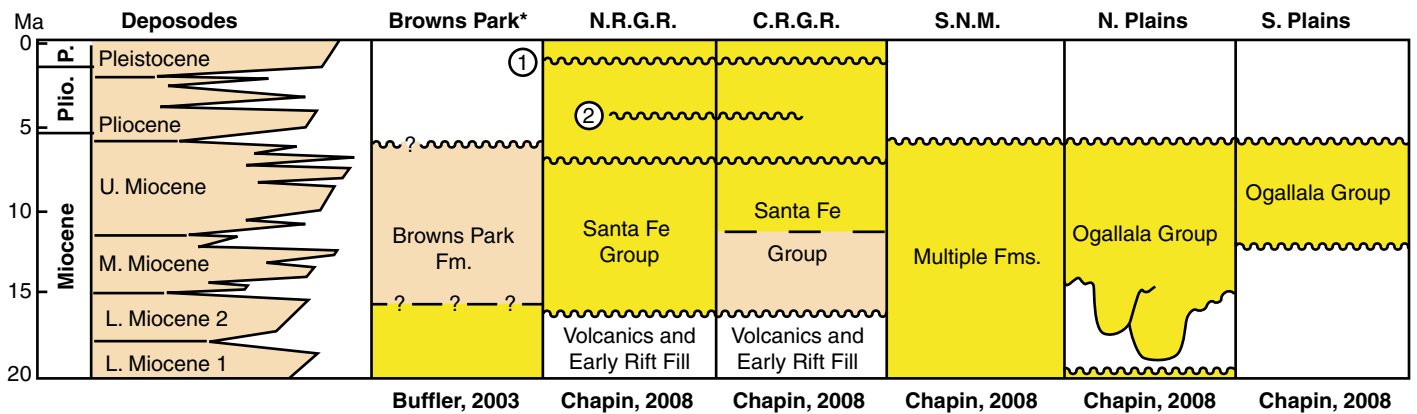
Figure 14. Early Miocene paleogeography. Compiled from Bart (1975), Scott (1982), Cather et al. (1994), Chapin and Cather (1994), Pazzaglia and Kelley (1998), Connell et al. (1999), Holm (2001), Buffler (2003), Cather et al. (2008), McMillan et al. (2006), and Flowers et al. (2008). For explanation see Figure 6.

Figure 15. Neogene sedimentary record of the Western Interior basins, Rio Grande Rift, and High Plains. Left column shows the correlative Gulf depositional episodes. Compiled from Buffler (2003) and Chapin (2008). Yellow indicates fluvial deposition; light brown reflects eolian strata.

(Galloway, 1982). To the east, warm temperate climate characterized the eastern Gulf coastal plain and Appalachian uplands.

Tributaries from both sides of the northern Rockies combined with flow gathered across the upper Midcontinent and eastern plateaus to form the axial Mississippi (Fig. 14). The Red River trunk stream collected tributaries that largely drained Rocky Mountain and remnant volcanic uplands of northern New Mexico. The nascent Rio Grande rift collected tributaries draining uplands of northwestern New Mexico and south central Colorado. Sediment known collectively as the Santa Fe Group (Fig. 15) accumulated in these closed basins, including the successor to the Laramide Galisteo. Surplus sediment likely bypassed the small rift basins. Headwaters of the Rio Grande fluvial axis tapped remnant uplands of the Mogollon volcanic field, active volcanic uplands of Trans-Pecos Texas, and eastern flanks of Basin and Range uplands (Fig. 14). Abundant volcanic rock fragments reflect these sources. The Rio Bravo continued to drain remnant basin-margin uplands and may have extended into the adjacent Basin and Range province. The Colorado Plateau was characterized by interior drainage, though little Early Miocene sediment is now found there. In central Arizona, a proto-Colorado drained southward, capturing the westernmost tributaries of the Oligocene Rio Grande. The continental divide likely extended along the axis of the remnant Oligocene volcanic uplands before diverting westward to the edge of the Basin and Range in Wyoming (Fig. 14).

In summary, competing processes and boundary conditions affected sediment supply rates and patterns of the Early Miocene. On the negative side, easily eroded volcanic uplands decreased in elevation, ash dispersal was greatly reduced, drainage basin area was somewhat decreased, local subsidence along the Rio Grande Rift began to sequester sediment, and the arid climate limited erosion and transport of sediment from the Western Interior. On the plus side, areas and rates of continental aggradation generally decreased, the erg was dissected, and extensive high-relief uplands remained as active sediment source areas. At first (LM 1), negative factors prevailed, and sediment supply to the GOM decreased (Fig. 1). Later in the Early Miocene (LM 2), however, the balance began to tip in favor of accelerated supply. Concomitantly, the eastern interior emerged as the dominant source area.

Middle Neogene Arid Extensional Era: Middle Miocene

Middle Miocene paleogeography reflects the culmination of Basin and Range extensional tectonics combined with a strong east-to-west climate gradient. The patterns established persisted with only modest change for nearly 12 million years.

The Middle Miocene Gulf coastal plain stratigraphy records three dominant fluvial/deltaic axes, two of which were new (Fig. 16) (Galloway, 2008). Such a dramatic change in the paleogeography of the receiving basin

strongly suggests equally significant changes in the source uplands and drainage basins. As described below, they did indeed occur. The Mississippi assumed its role as the dominant fluvial system in terms of sediment supply to the Gulf. However, a new system, with a drainage basin approximating that of the modern Tennessee River (Galloway, 2005b) arose immediately to the east of the Mississippi. The delta systems of the two rivers commonly merged, but the fluvial axes are distinct where they entered the paleocoastal plain. Sands of both are quartz rich (McBride et al., 1988), but those of the Tennessee are slightly more lithic. Both reflect mature, polycyclic continental source rocks. The Guadalupe axis, named for a modest, modern basin-margin counterpart, was characterized by its more diverse composition that includes common carbonate rock fragments.

Middle Miocene North America was hot. A warm temperate climate spread across the East and upper Midwest; the southeastern United States and lower Mississippi Valley were subtropical. The entire Western Interior and northwestern Gulf coastal plain was hot and arid (Hoel, 1982; Chapin, 2008). The middle Miocene deposode was coeval with the onset of renewed global cooling, following the Mid-Miocene climatic optimum (Zachos et al., 2001). It has been suggested that global change triggered regional climate attributes, such as increase in storm intensity or frequency, in the Appalachian uplands that, in turn, enhanced mechanical erosion rates and consequent sediment yield (Boettcher and Milliken, 1994).

Figure 16. Middle Miocene paleogeography. Compiled from Seni (1980), Scott (1982), Boreman et al. (1983, 1984), Gustavson and Winkler (1988), Brister and Gries (1994), Cather et al. (1994), Chapin and Cather (1994), Steven et al. (1997), Connell et al. (1999), Holm (2001), Buffler (2003), Chapin et al. (2004a), McMillan et al. (2006), Chapin (2008), and Flowers et al. (2008). For explanation see Figure 6.

The combination of tectonic and climatic events culminated in several responses that profoundly influenced drainage basin evolution and consequent pattern of sediment yield to the GOM. Three key elements of the continental interior drainage basins influenced ultimate sediment yield and transport axes (Fig. 16):

(1) Accelerated extension rate and consequent subsidence along the length of the Rio Grande Rift (Fig. 5) created a series of closed basins. This chain of basins extended from the Alamosa basin in southern Colorado to the Hueco bolson in Trans-Pecos Texas. It thus effectively insulated the Gulf margin from any upland lying west of the rift. The basins along the rift accumulated thick successions of continental sediment, known collectively as the Santa Fe Group (Fig. 15), derived from the adjacent rift shoulder uplifts and marginal volcanic uplands, both active and remnant.

(2) The arid climate and consequent low runoff limited fluvial sediment transport eastward from central and northern Rock Mountain sources. A series of aggrading distributive fluvial systems (terminology of Weissmann et al., 2010) merged to form the northern Ogallala alluvial apron (Figs. 15 and 16). Sediment aggraded, filled, and overflowed early Miocene erosional valleys as streams lost discharge to evaporation and infiltration and consequently to transport capacity (Chapin, 2008).

(3) Rejuvenated mechanical erosion of the Cumberland Plateau and Blue Ridge, which had remained insignificant sediment sources throughout the Paleogene, resulted in ~1 km of erosional unroofing of these uplands in the early Neogene (Boettcher and Milliken, 1994). A similar order-of-magnitude increase in sediment supply occurred on the Middle Atlantic margin (Poag and Sevon, 1989), demonstrating the regional impact of the erosional event. Indeed, the Middle–Upper Miocene was a time of dynamic global tectonic and climate reorganization (Cather et al., 2009; Potter and Szatmari, 2009).

The rejuvenated Appalachian uplands provide the runoff and sediment that elevated the Tennessee axis to prominence. As the Tennessee drainage basin matured, the Mississippi likely collected tributaries derived largely from the west. Central plains tributaries tapped the "leftovers" of the paleo North and South Platte systems, which together built much of the Ogallala apron (Fig. 16). To the south, a paleo Red River tapped the east flank of the southern Rockies. The Guadalupe axis peaked as a supplier of sediment to the northwestern GOM. The volumetric importance of this depocenter suggests a river that had integrated its drainage basin far beyond the nearby Edwards Plateau to incorporate distal uplands in Trans-Pecos Texas and east-central New Mexico. The Continental divide extended south along the crest of the Rockies and eastern rift flank uplands (Fig. 16). The Colorado Plateau contained several shallow closed lacustrine and alluvial basins; evaporation dominated. The Browns Park basins of the Colorado-Wyoming border (Fig. 15) accumulated eolian and shallow lake deposits.

The middle Miocene deposode was a time of high sediment influx into the GOM (Fig. 1, Table 1). At the same time, it records the full extent of the long-recognized shift of sediment accumulation from the western to the eastern Gulf. On the west, culmination of combined tectonic and climatic factors effectively reduced sediment supply. Western extent of Gulf-flowing drainage basins was truncated at the Rio Grande Rift. North of the Rift, extreme aridity created an energy-deficient alluvial regime; runoff was inadequate to the task of transporting coarse sediment more than a few hundred kilometers beyond the mountain front. It remained trapped in the continental interior as a broad alluvial apron. Contemporaneous climate change and/or tectonic uplift rejuvenated long dormant Appalachian uplands. The outpouring of sediment more than compensated for loss of sediment supply from the west. On balance, overall supply was nearly doubled, but the locus of accumulation was dramatically relocated.

Middle Neogene Arid Extensional Era: Late Miocene

The upper Miocene deposode mainly records an evolution of patterns that were well established in the middle Miocene (Fig. 17). The combined Mississippi and Tennessee axes produced the basin margin depocenter. The Guadalupe axis, though still present, declined in importance. Further southwest, the Rio Grande and Rio Bravo axes again reemerged as modest, but significant elements.

North American physiography was much the same, primarily reflecting distribution of uplands and basins established by earlier Miocene tectonism and climate (Fig. 17). The Rio Grande rift continued to subside, creating a series of closed basins that accumulated a mix of lacustrine, fluvial, and eolian fill. A northeast-southwest–trending belt of small to medium volcanic centers extended from the Springerville center in southeast Arizona to the Raton-Clayton in northeast New Mexico (Figs. 5 and 17). The central and southern Rocky Mountain front ranges continued to be elevated by rift shoulder uplift. Basin and Range uplift and faulting dominated the far west. Unroofing of the Appalachian uplands continued in the east.

The strong east-west zonal climate zones persisted. The Western Interior and northwest Gulf coastal plain remained arid, limiting runoff and enhancing evaporation (Chapin, 2008). Warm temperate conditions characterized the Midcontinent and northeastern Gulf margin. Northward, along the Appalachian trend, cool temperate conditions replaced warm temperate conditions of the earlier Miocene. Thus, drainage basins of the central and eastern continental interior received abundant discharge while river basins of the west were relatively runoff starved.

The Tennessee system continued to receive large volumes of runoff and quartz-rich sediment from the Cumberland Plateau and adjacent Appalachian terrains (Fig. 17). With headwaters in the well-watered east, it was the largest of the Late Miocene river systems in terms of sediment supply to the basin. The drainage basin of the Mississippi remained about the same as its earlier Miocene counterpart. However, overall supply of sediment decreased, as reflected in its devolution into the smaller of the central GOM systems. This reflects in part southward expansion of the aggrading Ogallala apron to include deposits of the paleo Arkansas and Canadian river systems (Figs. 16 and 17). Development of an aggrading distributive alluvial system by the Pecos deprived the paleo Guadalupe of runoff and sediment supply, resulting in its slow demise. Along the breadth of the Ogallala apron, sediments accumulated as runoff was lost to infiltration and evaporation as rivers flowed out of canyons onto the adjacent plains. The arid climate river systems were, in effect, energy deficient.

As in the Middle Miocene, the Rio Grande Rift created a moat and dam that together precluded sediment from the central and southern Western Interior from reaching the GOM (Fig. 17). To the west, drainage elements were trapped in closed lacustrine and eolian basins and in local grabens of the Basin and Range province. Rio Bravo presumably records integration of a basin-margin drainage basin in the adjacent Basin and Range province.

In summary, sediment supply to the GOM decreased significantly from its Middle Miocene peak (Fig. 1). The decrease reflects concordant effects of several factors: (1) Unroofing and uplift of Appalachian uplands was waning. (2) The Rio Grande Rift and remnant central Rocky Mountain uplands combined to insulate the GOM from any sediment supply from uplands of the Western Interior. (3) Along the eastern Rocky Mountain front limited precipitation and upland drainage basin area created energy-deficient rivers that deposited much of their entrained sediment along a 1500-km alluvial apron. Together the Miocene deposodes are an instructive example of the dynamic interplay
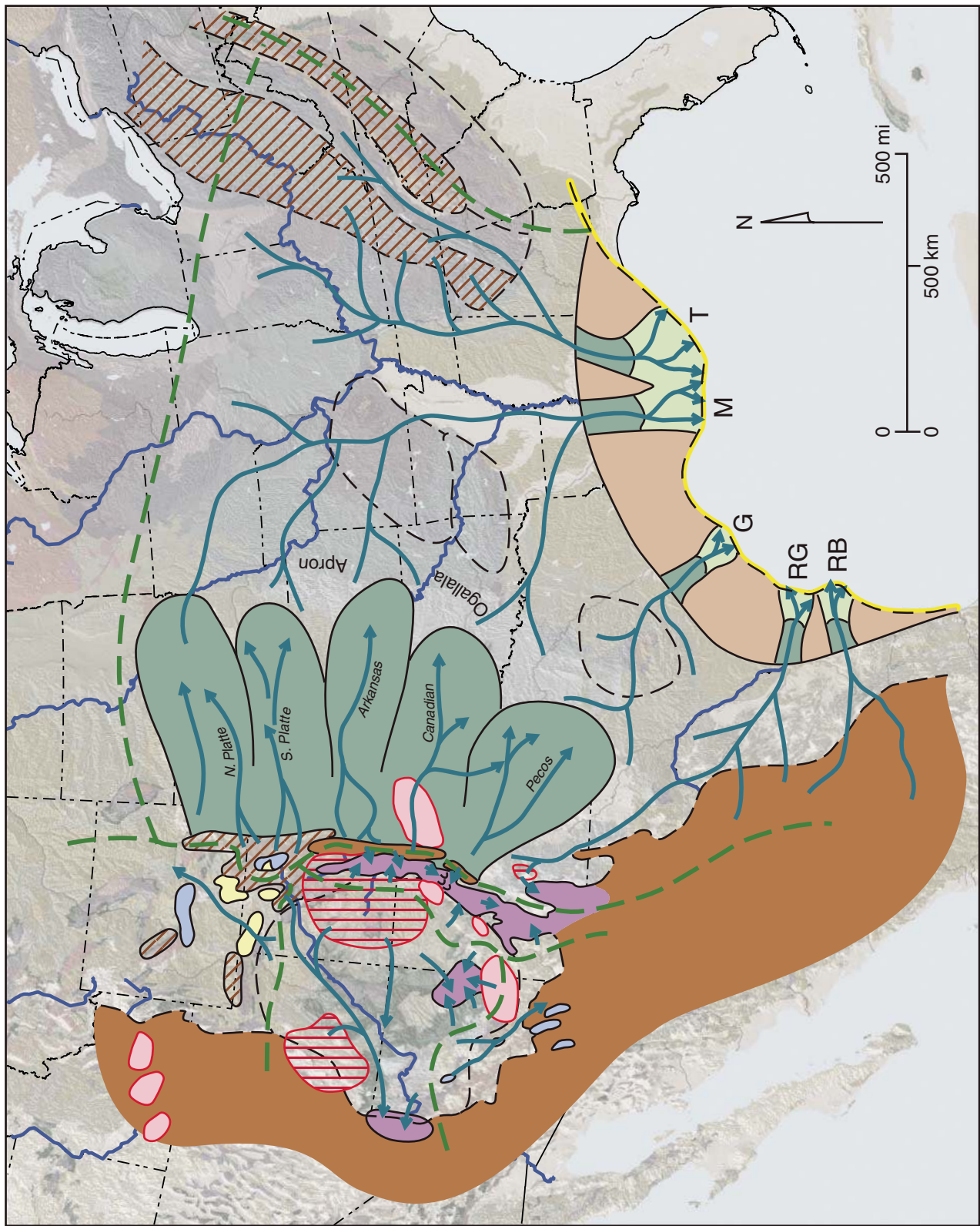
Figure 17. Late Miocene paleogeography. Compiled from Scott (1975), Seni (1980), Boreman et al. (1983, 1984), Gustavson and Winkler (1988), Brister and Gries (1994), Cather et al. (1994), Chapin and Cather (1994), Steven et al. (1997), Connell et al. (1999), Holm (2001), Perkins and Nash (2002), Buffler (2003), Mack (2004), Chapin et al. (2004a), McMillan et al. (2006), and Chapin (2008). For explanation see Figure 6.

between tectonism and climate in modulating sediment supply from a large and complex continental interior.

Late Neogene Monsoonal/Epeirogenic Uplift Era: Pliocene

The Plio-Pleistocene ushered in an era of landscape evolution across the North American interior. The configuration of uplands, drainage basins, and depositional elements assumed a modern aspect (Fig. 18). Critical changes included (1) modification of the climate regimes by introduction of Pacific moisture from the newly opening Gulf of California (Thompson, 1991; Chapin, 2008), (2) broad domal uplift of the Western Interior culminating in the broad, elevated Rocky Mountain Orogenic Plateau (Fig. 5) (McMillan et al., 2006; Eaton, 2008), and (3) global as well as local climatic cooling that led to glacioeustatic sea-level changes that increased in both frequency and amplitude (Molnar, 2004) and to formation of montane and then continental ice bodies across North America. Change (1) enhanced seasonal runoff, providing sufficient fluvial energy to both erode earlier Cenozoic alluvial and eolian basin fills and aprons and to again transport sediment to the ultimate receiving basin, the GOM. Change (2) further rejuvenated erosion in and around the Rocky Mountains, adjacent plains and basins, and Colorado Plateau. Change (3) enhanced climate instability, increased base-level change at the distal end of the drainage systems, and, finally, added ice to the mix of erosional agents supplying sediment to northern tributaries.

Deposition in the northern GOM was focused along the north-central basin margin where three extra-basinal rivers and their associated delta systems merged into a single regional depocenter (Fig. 18). The paleo Rio Bravo, Rio Grande, and Guadalupe rivers, though present, contributed proportionally little sediment to the basin. A new fluvial axis, however, appeared on the west flank of the Mississippi. It is named the Red River axis because its position on the Texas/Louisiana line approximates that of the late Quaternary Red River (before its permanent capture by the Mississippi Valley in the late Pleistocene [Saucier, 1994]).

Magnitude, timing, and cause of uplift of the Rocky Mountain orogenic plateau continue to be discussed and debated (see McMillan et al., 2006; Eaton, 2008). Regardless of specifics, the broad upland so defined is centered in southwestern Colorado and northwest New Mexico, where intermontane elevations exceed 2 km above sea level (Fig. 18). Along the east side of the Rocky Mountain chain, extending from eastern Wyoming to eastern New Mexico,

the High Plains are more than 1 km above sea level. Here, the western margin of the plains (the depositional surface of the Ogallala apron) was a focus for deep incision (Fig. 18) (McMillan et al., 2006). In general, widespread erosion followed the middle–late Miocene era of fluvial and eolian aggradation. Cutting north-to-south along the spine of the orogenic plateau, the Rio Grande Rift was the exception to the pattern. Basins along the rift continued to subside and efficiently store sediment from adjacent rift flanks. As the time passed, basins of the central rift began to fill and overflow south. However, this nucleus of what would become the modern Rio Grande River still terminated in closed basins, including the Hueco bolson (Fig. 5), at its southern end. At the north end of the rift, the Alamosa basin also remained closed. Small volcanic centers, including the Raton-Clayton, were active across northern New Mexico (Fig. 5).

The climate zones of the North American interior and Gulf Coast, as noted above, changed significantly relative to their Miocene precursors. Late Neogene global cooling was reflected in the spread of cool temperate conditions across the Rockies, Great Plains, Interior Lowland, Mississippi Valley, and Appalachians (Thompson, 1991). Tall grass prairie covered the interior plains of the continent (Retallack, 1997). The Gulf Coast remained warm, with a strong east-to-west zonation from wet temperate to warm subarid climates. Opening of the Gulf of California at ca. 6.4 Ma enhanced the spread of Pacific moisture northeastward across the Colorado Plateau and Rocky Mountains (Chapin, 2008). As the moist air encountered high elevations of the orogenic plateau, orographic lift created the summer monsoonal climate still present today. The rain shadow on the east side of the Rockies created a subarid climate.

Drainage basins responded in several ways to the mixture of climate and tectonic signals. The combination of the Rocky Mountain belt, crestal high of the orogenic plateau, and closed moat created by the still-active Rio Grande Rift insulated the GOM from all uplands further to the west (Fig. 18). The Pliocene saw the integration of the west-flowing Colorado River system across the Colorado Plateau. Tributaries flowing to the Gulf arose on the east side of the Rockies and plateau. The axial Rio Grande, though further integrated, terminated in the closed basins at the southern end of the rift system. The south-flowing Pecos River drainage system, now a major tributary to the Rio Grande, did develop along the east rift flank in southeastern New Mexico. However, source area and runoff remained inadequate to source a Rio Grande fluvial/deltaic depocenter in South

Texas. Tributaries arising along the east side of the Rocky Mountain drainage divide aggressively eroded and removed large areas of the subjacent Miocene Ogallala apron, particularly in Colorado and northeastern New Mexico (Fig. 18). Canyons and precursors of drainage elements, including the North and South Platte, and Arkansas can be recognized. The combined paleo Platte River flowed east, down the slope of the tilted high plains, providing a principal tributary to the axial Mississippi. The paleo Arkansas may also have followed the path of its modern counterpart to the Mississippi. However, Figure 18 suggests that it instead trended south eastward and merged with a paleo Canadian/Red river system to source the newly formed and prominent Red fluvial axis and depocenter. Capture of the Arkansas drainage would have directed sediment from the area of greatest erosional incision in southeast Colorado into the prominent Red fluvial/deltaic axis. This depocenter appeared at ca. 4 Ma. Although still present on the northeast Gulf margin, the Tennessee fluvial/deltaic axis continued to shrink. As supply from the Appalachians to the Atlantic increased in the Pliocene (Poag and Sevon, 1989), the decrease is interpreted to reflect expansion of the Mississippi drainage basin at the expense of that of the Tennessee.

The Pliocene saw a modest increase in sediment supply to the GOM (Fig. 1, Table 1). Climate change, by providing increased moisture, runoff, and seasonal flooding, enhanced the erosional and transport capacity of tributaries. Previously aggradational alluvial aprons along the Rocky Mountain front were dissected. Across the Colorado Plateau, streams incised the landscape. Erosion and effective eastward transport may also have been aided by further epeirogenic uplift of the Rocky Mountain Orogenic Plateau, with consequent tilting of the proximal High Plains (McMillan et al., 2002). These tributaries rejuvenated the nascent Red River fluvial/deltaic axis and augmented supply to the Mississippi axis from the Appalachians. The balance tipped slightly to greater sediment yield as the locus of source and supply shifted back somewhat to the west.

Late Neogene Monsoonal/Epeirogenic Uplift Era: Pleistocene

The Pleistocene would likely be undifferentiated from the Pliocene in this paper were it not for one additional geologic agent: ice. Ice in the form of mountain glaciers and a continental ice sheet became a primary erosional agent, modulated runoff, and, through its impact on intracontinental geomorphology, reshaped the drainage systems of North America.
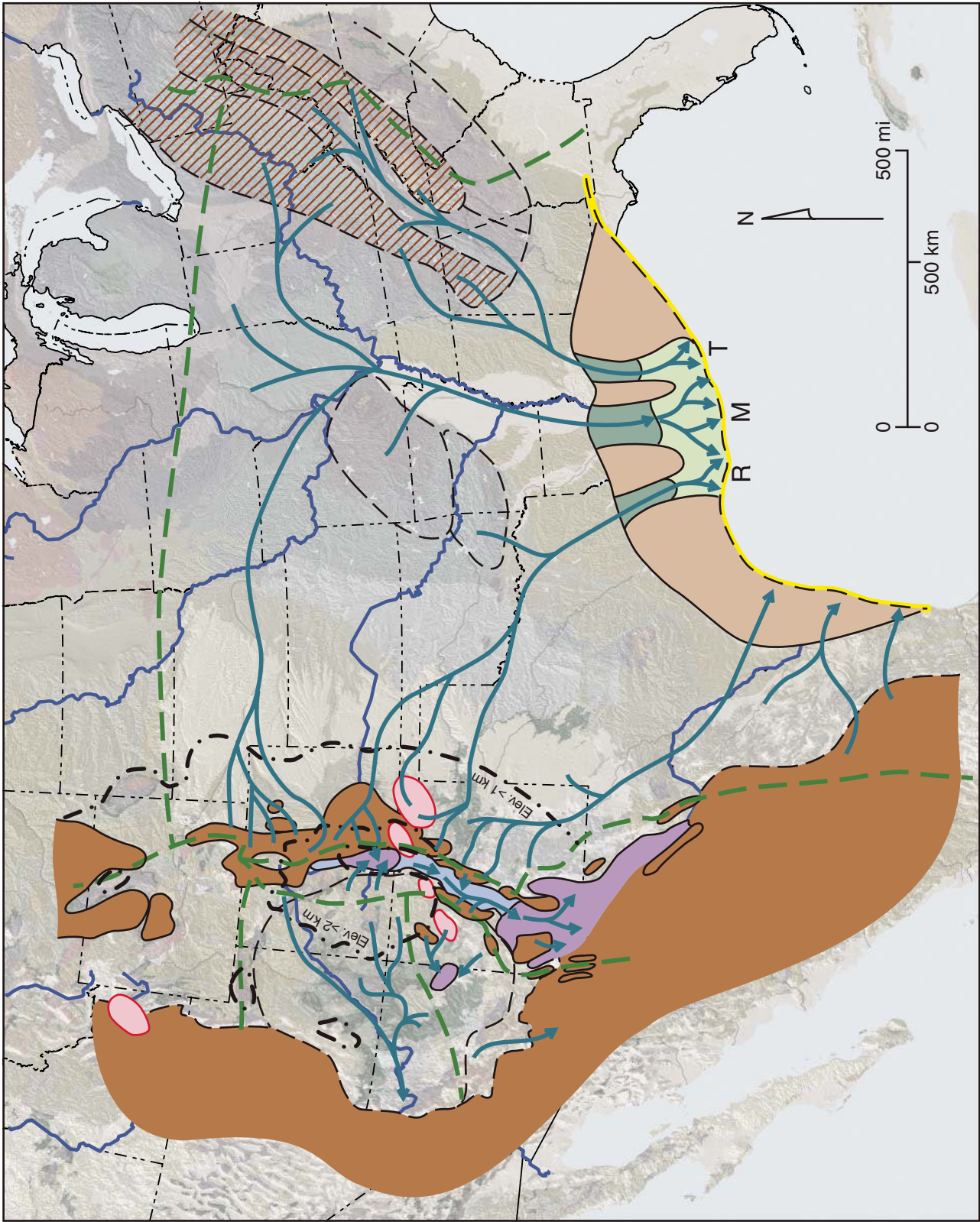
Figure 18. Pliocene paleogeography. Compiled from Scott (1975, 1982), Cather et al. (1994), Chapin and Cather (1994), Collins and Raney (1994), Lozinsky (1994), Connell et al. (1999), Perkins and Nash (2002), Dallege et al. (2003), Chapin et al. (2004a), Mack (2004), McMillan et al. (2006), Chapin (2008), and Flowers et al. (2008). For explanation see Figure 6.

Pleistocene depositional elements include continuations of the three central Gulf margin fluvial/deltaic axes: the Red, Mississippi, and Tennessee (Figs. 3 and 19). Through time, the Mississippi evolved into the prominent element, as the Red and Tennessee rivers were diverted into and captured by the incised Mississippi valley. A small, but identifiable Rio Grande system redeveloped on the south Texas coastal plain.

The tectonic framework of North America was little changed from that of the Pliocene. The Rio Grande Rift remained a prominent structural feature, but sediment accumulation finally exceeded subsidence. All but the northernmost Alamosa basin was integrated into a single, through-flowing fluvial system (Figs. 15 and 19). Initial Pleistocene erosion was followed by a later phase of mixed aggradation and down cutting. Small volcanic fields, including the Ocate-Raton and Yellowstone reflected the ongoing deep crustal processes that perpetuated Basin and Range extension.

The climate history was dominated by the development of the North American ice sheet and its repetitious advance and retreat from Canada (Fig. 19). Montane glaciation extended along the Rockies as far south as the Sangre de Cristo Mountains of northern New Mexico. Glacial outliers also covered the San Juans of southwestern Colorado, Uintas of northeastern Utah, and the Big Horn and Yellowstone Mountains of Wyoming. Although the northern Gulf margin retained a warm temperate climate, most of the continental interior and uplands were cool to cold. Continental glaciation commenced at ca. 2.4 Ma (Thompson, 1991), and is documented by the first appearance of meltwater runoff in the GOM (Galloway et al., 2000). The upper Midwest was proglacial tundra during times of ice sheet advance. Precipitation amount, seasonality, and geographic patterns changed repeatedly during glacial/interglacial cycles. At the same time, high-amplitude sea-level changes pushed fluvial/deltaic coastlines from near modern positions in interglacial periods to positions near modern shelf edges, more than a hundred kilometers seaward, during full glacial intervals.

The dominant themes in Pleistocene drainage basin evolution were the integration of numerous large drainage basins into a single axial Mississippi system and northward expansion of the Mississippi headwaters (Fig. 19). Several factors led to this convergence of drainage across the length and breadth of the continental interior.

(1) The long history of uplift of the Western Interior, culminating in the emergence of the Rocky Mountain Orogenic Plateau and the resultant tilting uplift of the western High Plains, created a ramp that directed rivers from the Platte to the Red more than 1000 km eastward from their headwater uplands.

(2) The ice sheet remolded drainage basin geomorphology across the upper Midwest, northern Great Plains, and Allegheny Plateau. Rivers were forced to drain south, away from or along the periphery of the ice sheet (Fig. 19). The modern Missouri and Ohio systems were created. Consequently, the east-west drainage divide separating rivers flowing south into the GOM and north toward the Arctic shifted dramatically northward.

(3) Cycles of ice sheet advance and retreat caused sympathetic cycles in water and sediment discharge through all glacially derived tributaries. These were collected by the Missouri and Ohio, which fed, in turn, into the Mississippi. Cycles of river incision and valley aggradation along the upper Mississippi ensued. From these cycles, a permanently entrenched Mississippi ultimately emerged, and this valley lowland repeatedly trapped flanking rivers, including the Red, Arkansas, and Tennessee (by the lower Ohio, which was in turn graded to the Mississippi Valley), creating the modern integrated drainage network (Saucier, 1994). As the different rivers merged into one, the composite Red/Mississippi/Tennessee delta merged into the single Mississippi delta system seen in the late Pleistocene–Holocene (Galloway et al., 2000).

The Platte, Arkansas, and Red rivers continued to actively erode the Ogallala and older alluvial aprons of the eastern Front Range (Fig. 19). With integration of an axial river flowing along the Rio Grande Rift, the continental divide shifted ~100 km west, to its present position on the western edge of the Colorado Plateau. The newly integrated Rio Grande emerged from the south end of the rift and turned toward the GOM. Along the way, it collected the Pecos and tributaries from northern Mexico; the Rio Grande and Rio Bravo became a single river. The combined system was adequate to produce a small fluvial/deltaic depocenter (Fig. 19).

Pleistocene sediment accumulation rates in the GOM are typical of global oceans in their record of extremely high values, more than double Pliocene rates (Fig. 1, Table 1) (Molnar, 2004). This increase is at least partly explained by the enhanced erosive capacity of ice. The upper Mississippi and the tributary Ohio and Missouri were repeatedly choked with braided glacial outwash, especially during periods of glacial retreat (Saucier, 1994; Rittenour et al., 2008). Glaciers sculpted the western mountains into their modern, rugged peaks. Tributaries and trunk channels of the Platte, Arkansas, Red, and Rio Grande remained or became dominantly erosional (Dethier, 2001). Given the minimal area of glaciation in uplands for many of these rivers, other climate factors dramatically enhanced erosion and bypass of sediment from diverse upland sources to the GOM sediment sink.

CONCLUSIONS

The Gulf of Mexico has served as the principal repository of sediment derived from the interior continental United States for the past 65 million years. Because it is a relatively small ocean basin with limited additional continental sediment source areas, the contribution from North America can be reasonably well delimited within the total basin fill. Regional well and seismic databases together document the distribution and thickness of age-defined stratal packages and provide the basis for interpreting and mapping their coastal plain paleogeography. Volumetric calculations for each package provide a first-order tabulation of sediment supply rates. The changing distribution of fluvial/deltaic sediment input axes and depocenters, in turn, provides a picture of the evolving location and relative importance of major extra-basinal rivers draining the various continental source areas. The sink component of a large and complex continental-scale source-to-sink couple is thus well defined. The delineation of the evolving source component, though complicated by limited preservation of the continental sedimentary record, has become increasingly possible with publication of critical syntheses of North American tectonic history, intracontinental sedimentation patterns, and geomorphic evolution. Compositional attributes further aid correlation of fluvial/deltaic axes to source areas. Both zircon dating and apatite fission track analysis have added new insights and show considerable promise.

Integration of the source elements and their history with depositional elements and history provides a picture of evolving Cenozoic continental sediment dispersal systems. The interplay of tectonics, climate, and geomorphic evolution can all be examined in the context of this interpreted history. Several conclusions and generalizations emerge.

(1) Sediment supply rate to the GOM, integrated over several million year intervals, has varied by as much as an order of magnitude through Cenozoic time. Supply rate has commonly varied by twofold between successive deposodes. Though absolute magnitudes are greater, reflecting greater basin and source area dimensions, this range of variability between depositional episodes is comparable to that seen in the Cenozoic North Sea basin fill (Liu and Galloway, 1997). Sediment supply is a significant, independent variable in the development
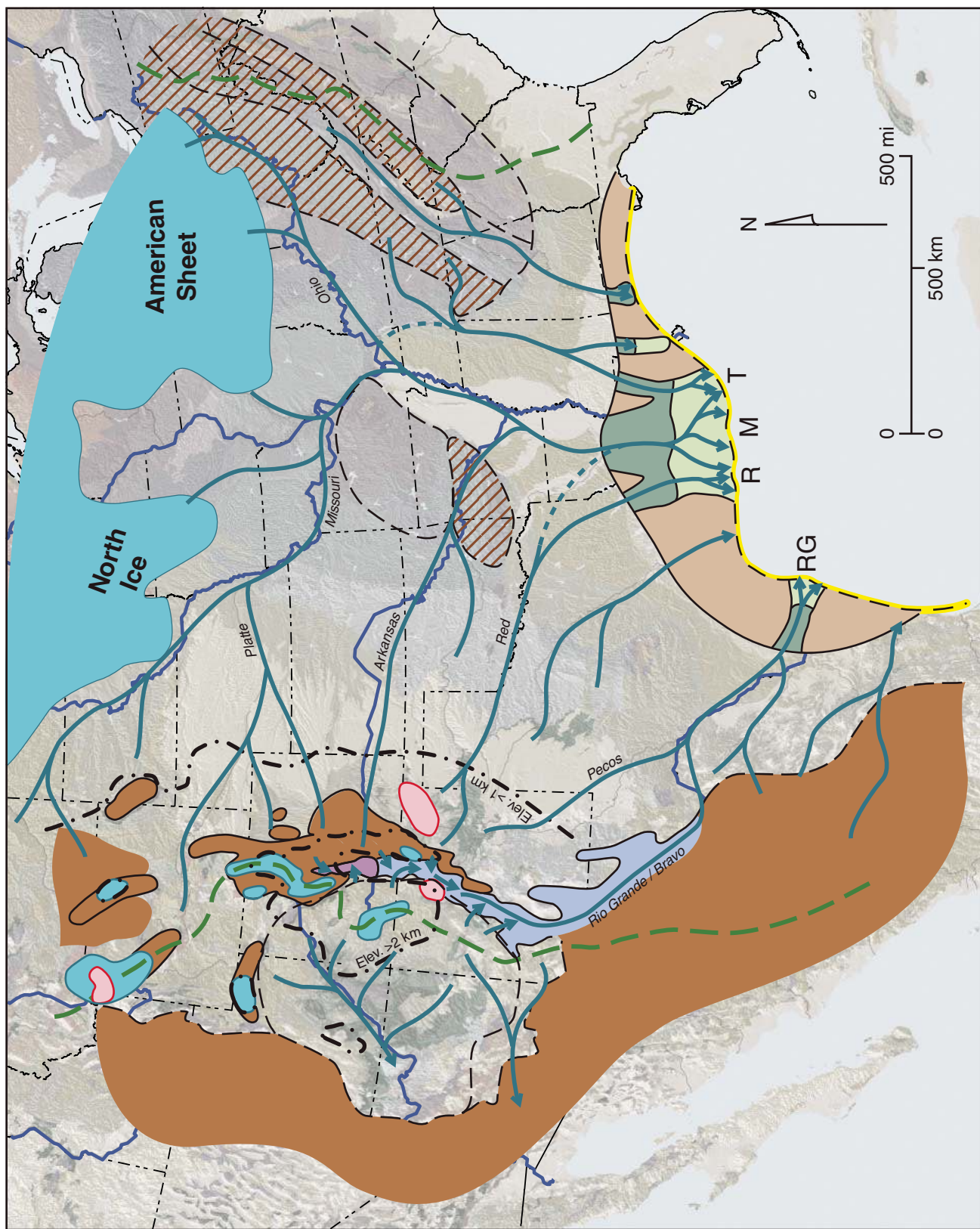
Figure 19. Pleistocene paleogeography. Compiled from Cather et al. (1994), Collins and Raney (1994), Chapin et al. (2004a), and McMillan et al. (2006). For explanation see Figure 6.

of stratigraphic sequences within the GOM basin (Galloway, 1989), older basins (Carvajal and Steel, 2009), and globally (Thorne and Swift, 1991; Catuneanu et al., 2009).

(2) Sediment supply to the GOM reflects the interplay of five variables: 1) areal extent of river drainage basins, 2) source area relief, 3) climate of the source areas and tributary systems, 4) lithology of the sediment sources, and 5) sediment storage within the drainage basin.

These are interdependent variables. Variables 1–3 encompass the fundamental controls of fluvial sediment load: area, elevation, runoff, and temperature (Syvitski and Milliman, 2007). The fourth reflects the balance between bedrock erosion versus recycling of older but unconsolidated sediments. The fifth is a product of the continental scale of the Gulf drainage basins and the geomorphic diversity of the landscapes upon which they are developed.

(3) Climate has played an important and complex role in modulating supply. Precipitation rate determined overall runoff. In wet tropical to temperate climate regimes, abundant runoff efficiently removed entrained sediment. Arid climate limited runoff; resultant transport-limited (Syvitski and Milliman, 2007) tributaries and trunk streams deposited aggradational alluvial aprons, storing sediment in the drainage basin even in the absence of a structural depression.
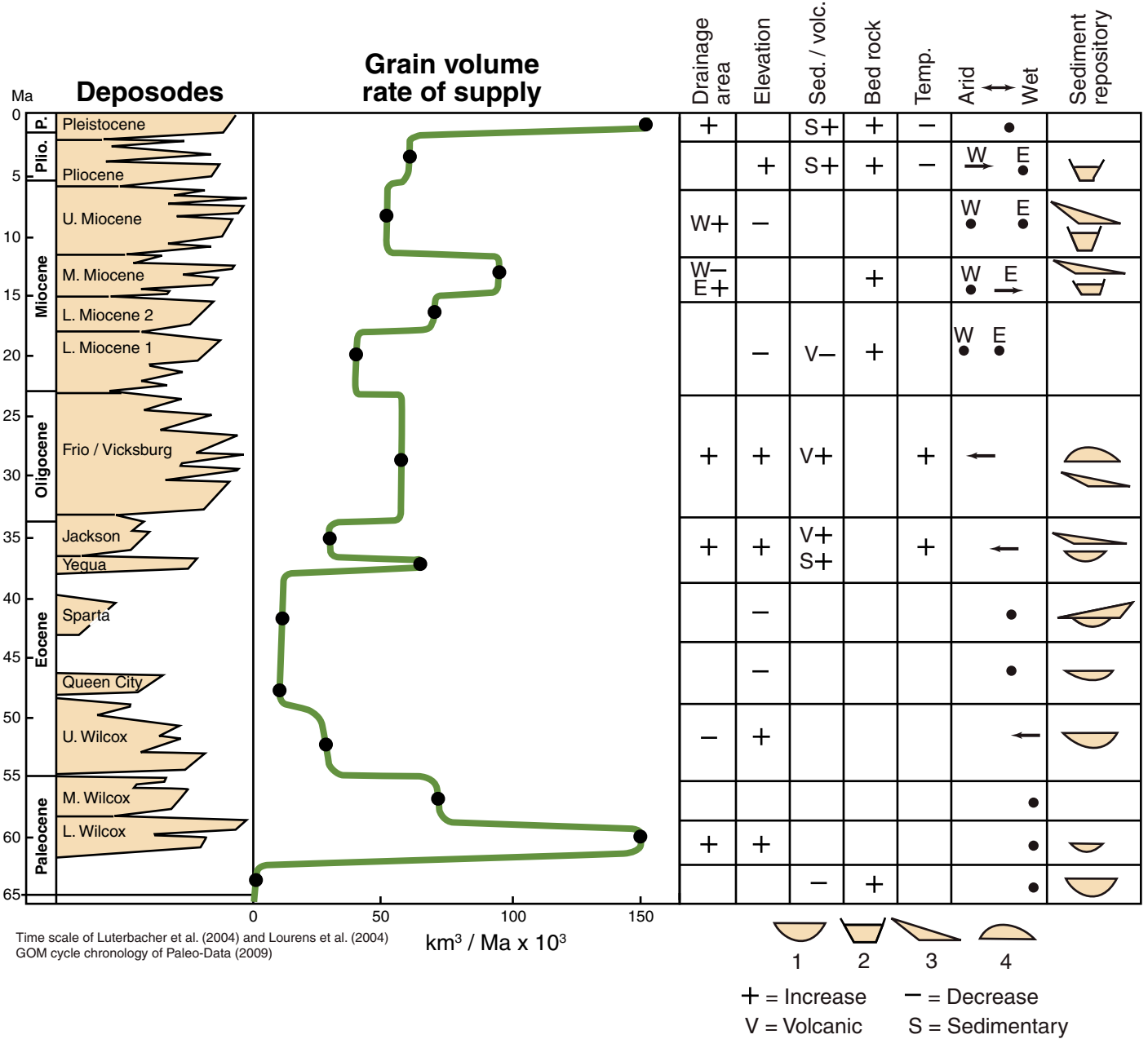

Figure 20. Summary chart for changes in variables potentially affecting overall sediment supply to the Gulf of Mexico basin. W or E in a cell indicates that the generality applies to the western or eastern interior drainage basins. Circles in the arid versus wet column indicate general climate during the depositional episode; arrows indicate direction of climate change relative to the preceding episode. Sediment repositories include: 1—Subsiding basins; 2—Fault-bounded rift basins; 3—Aggradational alluvial aprons; 4—Aggradational erg.

Eolian deposition commonly accompanied such alluvial aggradation. In contrast, seasonality and consequent runoff variability favored erosion and efficient sediment evacuation from the upper parts of drainage basins.

(4) Tectonism has played a prominent but equally complex role. Elevation of uplands by compression, crustal heating, or extrusive volcanism created primary loci of erosion and high sediment yield. At the same time, accompanying subsidence sometimes created long-term sediment repositories adjacent to sources. These structural depressions intercepted and sequestered much of that sediment. Regional patterns of uplift and subsidence relocated continental and regional drainage divides, reorganized drainage basin configurations, and diverted or redirected trunk stream paths to new points of entry along the Gulf margin.

(5) As predicted by modern sediment dispersal systems, large, integrated river systems emerging from continental drainage basins produce proportionally large shelf, slope, and basin-floor submarine fan systems (Sømme et al., 2009). Indeed, such large geomorphic elements characterized northern Cenozoic GOM submarine paleogeographies (Galloway et al., 2000).

Figure 20 summarizes qualitative changes in aggregate drainage basin size, source elevation, bedrock composition, paleoclimate of principal source area(s), intracontinental sediment repositories, and corresponding change in rate of sediment influx to the GOM. Influx rate is clearly a composite of multiple changes that may reinforce or diminish the final result. In general, the overview suggests that continental tectonics played a dominant role in the Paleocene–Middle Eocene deposodes, that climate became a significant control by late Eocene time, and that climate commonly dominated supply rate in the Neogene deposodes.

Finally, we emphasize that the reconstructions presented here remain a work in progress. Large parts of the tributary and axial trunk elements left no preserved geologic record. The record of most source areas is fragmented and incomplete. There is, and will remain, much educated guesswork in connecting GOM fluvial/deltaic depocenters to likely continental sources. However, there are many data to constrain choices and make such reconstructions worthwhile. New observations will continue to guide modification and improvement of such reconstructions.

APPENDIX: SEDIMENT VOLUME CALCULATION METHODOLOGY

Introduction

This appendix describes the methodology and procedure of application for computing volumes of sedi-

ment accumulation for deposodes in the Gulf of Mexico using Geographic Information Systems (GIS) software.

Methodology

In general, the methodology involves interpolating volumes of sediment accumulation from existing information in the form of borehole logs from wells and seismic survey data. Additional information comes in the form of literature published about the region and derived products such as isopach contours. In GIS format, these data become the inputs to volumetric calculations.

Because data sets such as borehole logs and isopach contours provide estimates of deposode thickness rather than volume, this methodology incorporates an intermediate step of interpolating rasters representing deposode thickness. One thickness raster is produced for each deposode. The thickness value for each grid cell within a given raster is then multiplied by the cell area (i.e., the raster cell size) to produce a raster where each cell's value represents the volume of sediment in that cell for the given deposode. These values are then summed to give a total volume for a given deposode. Because calculations utilizing grid cell areas are involved in this geospatial analysis, a projected coordinate system that preserves area was used.

The methodology for computing the volume of sediment accumulation for a given deposode was as follows.

(1) Compile sources of deposode thickness in GIS format.

(2) Choose an equal area coordinate system for the analysis.

(3) Project all GIS data for the analysis into the chosen coordinate system.

(4) Define the spatial extent of the analysis. This extent represents the areal extent of sediment in the deposode.

(5) Interpolate from deposode thickness values to produce a raster providing continuous values of thickness for the areal extent of the deposode.

(6) Multiply each cell in the thickness raster by the cell size to create a raster representing volume.

(7) Sum the values for all cells in the volume raster to produce a total volume for sediment accumulation for the deposode.

The resulting volume is uncorrected for compaction. To foster a better comparison of volumes across different units, one can use a general compaction factor such as current porosity, reflecting age and depth of burial for each unit. The grain volume, V_G, can then be computed and can be considered a corrected volume for the purposes of volume comparison. Alternatively, general compaction factors for age and/or depth of burial can be used. Derivation of compaction factors was beyond the scope of this study. The database used here does not contain information necessary for the calculation of GOM-specific compaction factors; generalized compaction factors were used.

Application Procedure

Compile Sources of Deposode Thickness

This project includes three data sets in geodatabase format, an Earth System Research Institute (ESRI) proprietary GIS format, pertinent to determination of deposode thickness:

(1) Locations of wells and their corresponding borehole logs from which deposode thickness values have been tabulated (Fig. A1).

(2) Discrete points sampled from seismic transects, for which seismic data have been interpreted and correlated to deposodes identified in wells (Fig. A1).

(3) Hand-drawn isopach contours derived from both well and shot point data used to reflect regional knowledge of Gulf of Mexico geology.

Choose a Coordinate System

Data were stored in a geographic coordinate system with thickness values in units of feet. These data must be transformed to an equal area projection. The projection used units of feet to be consistent. The Albers Equal Area projection using the North American Datum of 1983 (NAD83) is a common projection used for North American applications (U.S. Census Bureau, 2008; U.S. Geological Survey, 2005), and was chosen for this analysis. The three main properties that influence the appearance of the Albers Equal Area projection are the Central Meridian, Standard Parallel 1, and Standard Parallel 2. The center of the Gulf Basin Depositional Synthesis (GBDS) Project data base is roughly at –92° long, and so this value was used as the Central Meridian.

One method to calculate the standard parallels is by determining the range in latitude in degrees north to south and dividing this range by six. The "one-sixth rule" places the first standard parallel at one-sixth the range above the southern boundary and the second standard parallel minus one-sixth the range below the northern limit. Study area data points are bound roughly by latitudes of 19.5° and 32°. One-sixth of this range is ~2°, so the standard parallels chosen are 21.5° and 30°.

The remaining Albers Equal Area parameters (False Easting, False Northing, Latitude of Origin), along with the Central Meridian, only affect x and y values of the coordinate grid; therefore, the choice of values for this parameters does not affect the analysis. The properties of the coordinate system are summarized in Table A1.

Project Data to the GBDS Albers Equal Area Projection

A convenient way to set a projection in ArcGIS is to define the projection on a feature data set and then store geospatial features within the feature data set. When features are imported into the feature data set, ArcGIS automatically reprojects the data to match the feature data set's coordinate system. This approach was used. The steps are:

(1) Open ArcCatalog, the data management application in ArcGIS.

(2) Create a new geodatabase named Analysis for the volumetric analysis.

(3) Create a new feature data set named GbdsAlbers within the geodatabase.

(4) Apply the study-specific Albers Equal Area projection to the feature data set.

(5) Copy and paste the original data into the feature data set. This automatically reprojects the data to match the feature data set's coordinate system.

Defining Analysis Extent

For each deposode, the areal extent of analysis must be defined. This extent reflects what is presumed to be the extent of the deposode based on known data, literature, and expert knowledge. The analysis extents were manually digitized and stored as polygons in the GbdsAlbers feature data set. These extents exhibit themselves as the boundaries of the resulting thickness rasters, as shown in subsequent figures in this text.

Interpolate Thickness Rasters

The study database includes point locations (wells and shot points) and linear features (isopach contours) recording thickness values that can be used to drive an
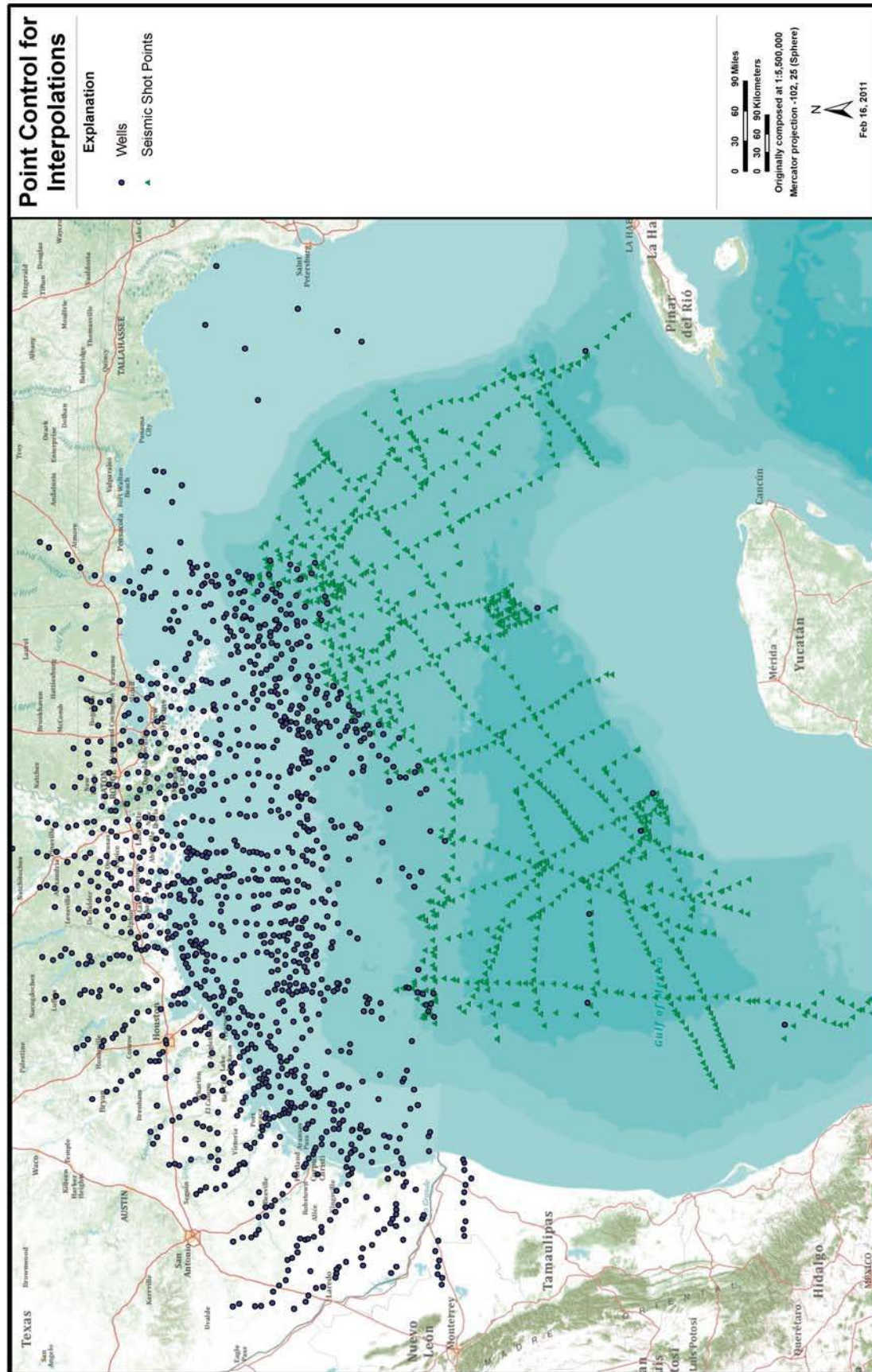
Figure A1. Location of all data points used for measurement of deposode thickness.

Geosphere, August 2011

TABLE A1. ALBERS EQUAL AREA PROJECTION PROPERTIES

Property	Value
Projection	Albers
False Easting	0.0
False Northing	0.0
Central Meridian	−92.0
Standard Parallel 1	21.5
Standard Parallel 2	30.0
Latitude of Origin	23.0
Linear unit	Foot
Datum	NAD83

interpolation. It was necessary to include the contours in the analysis because they not only provide control beyond the point data, but also take into account expert knowledge that cannot be gleaned from the point data alone.

ArcGIS includes a tool called Topo To Raster, which can interpolate from both point and contour data. The algorithms used by this tool were originally developed to compute digital elevation models suitable for hydrologic analysis, but the tool has found good application in other domains as well. Details of the algorithm are provided by ESRI (2007). In setting up the Topo To Raster tool for a given deposode, the well and shot point data were selected as point elevation inputs, and the isopach contours were selected as contour inputs. The polygon representing areal extent of the deposode is selected as the boundary for the interpolation. Additional parameters are shown in Table A2. The Topo To Raster tool was then run for each deposode, resulting in a suite of deposode thickness rasters.

Compute Volume

The output of the Topo To Raster tool is a raster depicting the thickness of the given deposode, which was then multiplied by the raster cell size to compute volume. The procedure to compute volume for a given deposode using ArcMap, the analysis application in ArcGIS, is outlined below.

(1) Use the ArcGIS Zonal Statistics tool to compute zonal statistics using the deposode thickness raster as the input values and the boundary polygon as the zone. The output is a table with a field called Sum that contains the sum of all thickness values in feet.

(2) Add a field to this table called VolCubicFt.

(3) Calculate VolCubicFt = Sum * 3281 * 3281. (3281 ft was the raster cell size.)

Results of the volume calculation are shown in Table 1A.

Appendix References Cited

ESRI, 2007, Hydrologically correct surfaces: Topo to Raster: http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Hydrologically_correct_surfaces%3A_Topo_to_Raster (Accessed February 12, 2011).

ESRI, 2008, Albers Equal Area Conic: http://webhelp.esri.com/ARCGISDESKTOP/9.3/index.cfm?TopicName=Albers_Equal_Area_Conic (Accessed February 12, 2011).

U.S. Census Bureau, 2008, Projection information for the cartographic boundary files: Geography Division, Cartographic Products Management Branch: http://www.census.gov/geo/www/cob/projection.html (Accessed February 12, 2011).

U.S. Geological Survey, 2005, Decision support system for map projections of small scale data: http://mcmcweb.er.usgs.gov/DSS/ImgHTML/Albers.html (Accessed February 12, 2011).

REFERENCES CITED

Bart, H.A., 1975, Miocene sediment dispersal for western Nebraska and south-eastern Wyoming: Contributions to Geology (Copenhagen), v. 14, p. 27–39.

Boettcher, S.S., and Milliken, K.L., 1994, Mesozoic-Cenozoic unroofing of the southern Appalachian Basin: Apatite fission track evidence from Middle Pennsylvanian sandstones: The Journal of Geology, v. 102, p. 655–663, doi: 10.1086/629710.

Bolroyd, D.W., 1997, Late Cenozoic history of the Northern Colorado Front Range, *in* Colorado Front Range guidebook: Denver, Colorado, Rocky Mountain Association of Geologists, p. 125–133.

Boreman, R.G., Lindner, J.B., Bryn, S.M., and Rutledge, J., 1983, The Ogallala aquifer in the Northern High Plains of Colorado-saturated thickness in 1980; saturated-thickness changes, predevelopment to 1980; hydraulic conductivity; specific yield; and predevelopment and 1980 probable well yields: U.S. Geological Survey Hydrologic Investigations Atlas HA-671.

Boreman, R.G., Meredith, T.S., and Bryn, S.M., 1984, Geology, altitude, and depth of the bedrock surface; altitude of the water table in 1980; and saturated thickness of the Ogallala aquifer in 1980 in the southern High Plains of Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-673.

Brister, B.S., and Gries, R.R., 1994, Tertiary stratigraphy and tectonic development of the Alamosa basin (northern San Luis Basin), Rio Grande rift, south-central Colorado, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, stratigraphy, and tectonic setting: Boulder, Colorado, Geological Society of America Special Paper 291, p. 39–58.

Buffler, R.T., 2003, The Browns Park Formation in the Elkhead region, northwestern Colorado-south central Wyoming: Implications for late Cenozoic sedimentation, *in* Raynolds, R.G., and Flores, R.M., eds., Cenozoic systems of the Rocky Mountain region: Denver, Colorado, Rocky Mountain SEPM, p. 184–212.

Carroll, A.R., Chetel, L.M., and Smith, M.E., 2006, Feast to famine: Sediment supply control on Laramide basin fill: Geology, v. 34, p. 197–200, doi: 10.1130/G22148.1.

Carvajal, C., and Steel, R., 2009, Shelf-edge architecture and bypass of sand to deep water: Influence of shelf-edge processes, sea level, and sediment supply: Journal of Sedimentary Research, v. 79, p. 652–672, doi: 10.2110/jsr.2009.074.

Cather, S.M., 2004, Laramide orogeny in central and northern New Mexico and southern Colorado, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico: A geologic history: New Mexico Geologic Society Special Publication 11, p. 203–248.

TABLE A2. TOPO TO RASTER PARAMETERS FOR DEPOSODE THICKNESS INTERPOLATION

Parameter	Value	Notes
Cell size	3281 ft (1 km)	This cell size is less than the typical spacing of wells in the Gulf of Mexico, yet not so fine as to be computationally prohibitive.
Output extent	Same as boundary polygon	
Margin in cells	20	Analysis will extend this number of cells beyond the boundary to produce a smoother result at the boundary.
Smallest *z* value	0	Thickness values less than zero do not make sense, so a minimum thickness value of zero is set to constrain the interpolation.
Largest *z* value	20% above the largest input value	This is the default value.
Drainage enforcement	NO_ENFORCE	This flag indicates that hydrologic drainage should not be enforced. Enforcing drainage patterns would not make sense for thickness interpolations.
Primary type of input data	CONTOUR	Because contours reflect expert knowledge as well as known data, they are given more weight in the interpolation.
Maximum number of iterations	40	Values higher than this default value are only recommended for hydrologic analyses involving sinks or if better defined streams and ridges are desired.
Roughness penalty	Default	Lower values produce artificial peaks and troughs, while higher values result in smoother interpolation results. Leave as the default, which lets the software decide on a value based on the primary type of input data.
Discretization error factor	0.5	Higher values mean more smoothing. Use the minimum recommended value of 0.5.
Vertical standard error	0	This takes into account random error in the data, typically resulting in smoother elevation shifts for higher values of error. For this analysis, the resulting raster should strictly honor wells and contours, so this parameter is left as the default of zero.
Tolerance 1 / Tolerance 2	Default	Irrelevant since sinks are not enforced.

Cather, S.M., and Chapin, C.E., 1990, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Alternative interpretation and reply: Geological Society of America Bulletin, v. 102, p. 256–260, doi: 10.1130/0016-7606(1990)102<0256:PAPSOL>2.3 .CO;2.

Cather, S.M., and Johnson, B.D., 1984, Eocene tectonics and depositional setting of west-central New Mexico and eastern Arizona: New Mexico Bureau of Mines and Mineral Resources Circular 192, 33 p.

Cather, S.M., Chamberlin, R.M., Chapin, C.E., and McIntosh, W.C., 1994, Stratigraphic consequences of episodic extension in the Lemitar Mountains, central Rio Grande rift, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, stratigraphy, and tectonic setting: Boulder, Colorado, Geological Society of America Special Paper 291, p.157–169.

Cather, S.M., Connell, S.D., Chamberlin, R.M., McIntosh, W.C., Jones, G.E., Potochnik, A.R., Lucas, S.G., and Johnson, P.S., 2008, The Chuska erg: Paleogeomorphic and paleoclimatic implications of an Oligocene sand sea on the Colorado Plateau: Geological Society of America Bulletin, v. 120, p. 13–33.

Cather, S.M., Dunbar, N.W., McDowell, F.W., McIntosh, W.C., and Scholle, P.A., 2009, Climate forcing by iron fertilization from repeated ignimbrite eruptions: The icehouse-silicic large igneous province (SLIP) hypothesis: Geosphere, v. 5, p. 315–324, doi: 10.1130/ GES00188.1.

Catuneanu, O., Abrue, V., Bhattacharya, J.P., et al., 2009, Towards the standardization of sequence stratigraphy: Earth-Science Reviews, v. 92, p. 1–33, doi: 10.1016/j .earscirev.2008.10.003.

Chapin, C.E., 2008, Interplay of oceanographic and paleoclimate events with tectonism during middle to late Miocene sedimentation across the southwestern USA: Geosphere, v. 4, p. 976–991, doi: 10.1130/ GES00171.1.

Chapin, C.E., and Cather, S.M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, stratigraphy, and tectonic setting: Boulder, Colorado, Geological Society of America Special Paper 291, p. 5–25.

Chapin, C.E., Wilks, M., and McIntosh, W.C., 2004a, Space-time patterns of late Cretaceous to present magmatism in New Mexico—Comparison with Andean volcanism and potential for future volcanism: Socorro: New Mexico Bureau of Geology and Mineral Resources Bulletin, v. 160, p. 13–40.

Chapin, C.E., McIntosh, W.C., and Chamberlin, R.M., 2004b, The late Eocene-Oligocene peak of Cenozoic volcanism in southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico: A geologic history: New Mexico Geologic Society Special Publication 11, p. 271–293.

Chase, C.G., Gregory-Wodzicki, K.M., Parrish, J.T., and DeCelles, P.G., 1998, Topographic control of the western Cordillera of North America and controls on climate, *in* Crowley, T.J., and Burke, K.C., eds., Tectonic boundary conditions for climate reconstructions: New York, Oxford University Press, p. 73–99.

Christiansen, R.L., and Yeats, R.S., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran orogeny: Coterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3, p. 261–406.

Clark, J.C., 1975, Controls of sedimentation and provenance of sediments in the Oligocene of the central Rocky Mountains, *in* Curtis, F.B., ed., Cenozoic history of the southern Rocky Mountains: Boulder, Colorado, Geological Society of America Memoir 144, p. 95–117.

Collins, E.W., and Raney, J.A., 1994, Tertiary and Quaternary tectonics of the Hueco bolson, Trans-Pecos Texas and Chihuahua, Mexico, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, stratigraphy, and tectonic setting: Boulder, Colorado, Geological Society of America Special Paper 291, p. 265–282.

Combellas-Bigott, R.I., and Galloway, W.E., 2005, Depositional and structural evolution of the middle Miocene depositional episode, east-central Gulf of Mexico: The American Association of Petroleum Geologists Bulletin, v. 90, p. 335–362.

Connell, S.D., Koning, D.J., and Cather, S.M., 1999, Revisions to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque basin, New Mexico, *in* Albuquerque Geology: New Mexico Geological Society Guidebook, 50th Field Conference, p. 337–350.

Dallege, T.A., Ort, M.H., McIntosh, W.C., and Perkins, M.E., 2003, Mio-Pliocene chronostratigraphy, basin morphology and paleodrainage relations derived from the Bidahochi Formation, Hopi and Navajo Nations, northeastern Arizona: The Mountain Geologist, v. 40, p. 55–82.

Davis, S.J., Mulch, A., Carroll, A.R., Horton, T.W., and Chamberlain, P.C., 2009, Paleogene landscape evolution of the central North American Cordillera: Developing topography and hydrology in the Laramide Foreland Geological Society of America Bulletin, v. 121, p. 100–116.

Dethier, D.P., 2001, Pleistocene incision rates in the western United States calibrated using Lava Creek B tephra: Geology, v. 29, p. 783–786, doi: 10.1130/0091-7613(2001)029<0783:PIRITW>2.0 .CO;2.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039, doi: 10.1130/0016-7606(1988)100<1023:PAPSOL>2.3 .CO;2.

Eaton, G.P., 2008, Epeirogeny in the southern Rocky Mountains region: Evidence and origin: Geosphere, v. 4, p. 764–784, doi: 10.1130/GES00149.1.

Ellis, B., Johnson, K.R., and Dunn, R.E., 2003, Evidence for an in situ early Paleocene rainforest from Castle Rock, Colorado: Rocky Mountain Geology, v. 38, p. 73–100, doi: 10.2113/gsrocky.38.1.173.

Epis, R.C., and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post-Laramide, Late Eocene erosion surface in the southern Rocky Mountains, *in* Curtis, F.B., ed., Cenozoic history of the southern Rocky Mountains: Boulder, Colorado, Geological Society of America Memoir 144, p. 1023–1039.

Evanoff, E., 1990, Early Oligocene paleovalleys in southern and central Wyoming: Evidence of high local relief on the late Eocene unconformity: Geology, v. 18, p. 443–446, doi: 10.1130/0091-7613(1990)018<0443: EOPISA>2.3.CO;2.

Fan, M., and Dettman, D.L., 2009, Late Paleocene high Laramide ranges in northeast Wyoming: Oxygen isotope study of ancient river water: Earth and Planetary Science Letters, v. 286, p. 110–121, doi: 10.1016/j .epsl.2009.06.024.

Fassett, J.E., 1985, Early Tertiary paleogeography and paleotectonics of the San Juan Basin area, New Mexico and Colorado, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of west-central United States: Denver, Colorado, Rocky Mountain Section SEPM, p. 317–334.

Ferrari, L., Lopez-Martinez, M., Aguirre-Diaz, G., and Carrasco-Nunez, G., 1999, Space-time patterns of Cenozoic arc volcanism in central Mexico: From the Sierra Madre Occidental to the Mexican Volcanic Belt: Geology, v. 27, p. 303–306, doi: 10.1130/0091-7613(1999)027<0303:STPOCA>2.3 .CO;2.

Flores, R.M., 2003, Paleocene paleogeographic, paleotectonic, and paleoclimatic patterns of the northern Rocky Mountains and Great Plains region, *in* Raynolds, R.G., and Flores, R.M., eds., Cenozoic systems of the Rocky Mountain region: Denver, Colorado, Rocky Mountain Section SEPM, p. 63–106.

Flowers, R.M., Wernicke, B.P., and Farley, K.A., 2008, Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry: Geological Society of America Bulletin, v. 120, p. 571–587, doi: 10.1130/B26231.1.

Galloway, W.E., 1977, Catahoula Formation of the Texas coastal plain: Depositional systems, composition, structural development, ground-water flow history, and uranium distribution: Bureau of Economic Geology, The University of Texas at Austin, Report of Investigations No. 87, 59 p.

Galloway, W.E., Henry C.D., and Smith, G.E., 1982, Depositional framework, hydrostratigraphy, and uranium mineralization of the Oakville Sandstone (Miocene), Texas coastal plain: Bureau of Economic Geology, The University of Texas at Austin, Report of Investigations No. 113, 51 p.

Galloway, W.E., 1981, Depositional architecture of Cenozoic Gulf Coastal Plain fluvial systems: Society of Economic Paleontologists and Mineralogists Special Publication No. 31, p. 127–155.

Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding-surface bounded depositional units: The American Association of Petroleum Geologists Bulletin, v. 73, no. 2, p. 125–142.

Galloway, W.E., 2002, Cenozoic evolution of sediment accumulation in deltaic and shore-zone depositional systems, northern Gulf of Mexico basin: Marine and Petroleum Geology, v. 18, p. 1031–1040, doi: 10.1016/ S0264-8172(01)00045-9.

Galloway, W.E., 2005a, Cenozoic evolution of the northern Gulf of Mexico continental margin, *in* Gulf Coast Section SEPM 25th Annual Research Conference Proceedings, p. 1–15.

Galloway, W.E., 2005b, Gulf of Mexico basin depositional record of Cenozoic drainage basin evolution, *in* Blum, M.D., Marriott, S.B., and Leclair, S.F., Fluvial sedimentology VII: Malden Massachusetts, International Association of Sedimentologists Special Publication 35, p. 409–423.

Galloway, W.E., 2008, Depositional evolution of the Gulf of Mexico sedimentary basin, *in* Hsü, K.J., ed., Sedimentary basins of the world, Volume 5, The sedimentary basins of the United States and Canada, Miall, A.D., ed.: The Netherlands, Elsevier, p. 505–549.

Galloway, W.E., and Williams, T.A., 1991, Sediment accumulation rates in time and space: Paleogene genetic stratigraphic sequences of the northwestern Gulf of Mexico basin: Geology, v. 19, p. 986–989, doi: 10.1130/0091-7613(1991)019<0986:SARITA>2.3 .CO;2.

Galloway, W.E., Ganey-Curry, P.E., Li, X., and Buffler, R.T., 2000, Cenozoic depositional history of the Gulf of Mexico basin: The American Association of Petroleum Geologists Bulletin, v. 84, p. 1743–1774.

Gustavson, T.C., and Winkler, D.A., 1988, Depositional facies of the Miocene-Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico: Geology, v. 16, p. 203–206.

Hamlin, H.S., 1988, Depositional and ground-water flow systems of the Carrizo-Upper Wilcox, South Texas: Bureau of Economic Geology, The University of Texas at Austin, Report of Investigations No. 175, 61 p.

Hoel, H.D., 1982, Goliad Formation of the south Texas gulf coastal plain [unpublished M.S. thesis]: University of Texas at Austin, 126 p.

Holm, R.F., 2001, Cenozoic paleogeography of the central Mogollon Rim-southern Colorado Plateau region, Arizona, revealed by Tertiary gravel deposits, Oligocene to Pleistocene lava flows, and incised streams: Geological Society of America Bulletin, v. 113, p. 1467–1485, doi: 10.1130/0016-7606(2001)113<1467:CPOTCM> 2.0.CO;2.

Hutto, A.P., Yancey, T.E., and Miller, B.V., 2009, Provenance of Paleocene-Eocene Wilcox Group sediments in Texas: The evidence from detrital zircons: Gulf Coast Association of Geological Societies Transactions, v. 59, p. 357–362.

Kelley, S.A., and Chapin, C.E., 2004, Denudation history and internal structure of the Front Range and Wet Mountains, Colorado, based on apatite-fission-track thermochronology: New Mexico Bureau of Geology and Mineral Resources Bulletin, v. 160, p. 41–77.

Larsen, E.E., and Evanoff, E., 1998, Tephrostratigraphy and source of the tuffs of the White River sequence, *in* Terry, D.O., Jr., LaGarry, H.E., and Hunt, R.M., Jr., Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America):

Boulder, Colorado, Geological Society of America Special Paper 325, p. 1–14.

Lawton, T.F., 2008, Laramide sedimentary basins, *in* Hsü, K.J., ed., Sedimentary basins of the world, Volume 5, The sedimentary basins of the United States and Canada, Miall, A.D., ed.: The Netherlands, Elsevier, p. 429–450.

Lawton, T.F., Bradford, I.A., Vega, F.J., Gehrels, G.E., and Amato, J.M., 2009, Provenance of Upper Cretaceous-Paleogene sandstones in the foreland basin system of the Sierra Madre Oriental, northeastern Mexico, and its bearing on fluvial dispersal systems of the Mexican Laramide Province: Geological Society of America Bulletin, v. 121, p. 820–836, doi: 10.1130/B26450.1.

Lehman, T.M., 1991, Sedimentation and tectonism in the Laramide Tornillo Basin of West Texas: Sedimentary Geology, v. 75, p. 9–28, doi: 10.1016/0037-0738(91)90047-H.

Lillegraven, J.A., and Ostresh, L.M., Jr., 1988, Evolution of Wyoming's early Cenozoic topography and drainage patterns: National Geographic Research, v. 4, p. 303–327.

Liu, X., and Galloway, W.E., 1997, Quantitative determination of Tertiary sediment supply to the North Sea Basin: The American Association of Petroleum Geologists Bulletin, v. 81, p. 1482–1509.

Loucks, R.G., Dodge, M.M., and Galloway, W.E., 1986, Controls on porosity and permeability of hydrocarbon reservoirs in lower Tertiary sandstones along the Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 149, 78 p.

Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J., and Wilson, D., 2004, The Neogene Period, *in* Gradstein, F.M., Ogg, J.G., and Smith, A.G., eds., A geologic time scale 2004: Cambridge, Cambridge University Press, p. 409–440.

Lozinsky, R.P., 1994, Cenozoic stratigraphy, sandstone petrology, and depositional history of the Albuquerque Basin, central New Mexico, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, stratigraphy, and tectonic setting: Boulder, Colorado, Geological Society of America Special Paper 291, p. 73–81.

Luterbacher, H.P., Ali, J.R., Brinkhuis, H., Gradstein, F.M., Hooker, J., Monechi, S., Ogg, J.J., Powell, J., Rohl, U., Sanfilippo, A., and Schmitz, B., 2004, The Paleogene Period, *in* Gradstein, F.M., Ogg, J.G., and Smith, A.G., eds., A geologic time scale 2004: Cambridge, Cambridge University Press, p. 384–408.

Mack, G.H., 2004, Middle and Late Cenozoic crustal extension, sedimentation, and volcanism in the southern Rio Grande Rift, Basin and Range, and southern transition zone of southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico: A geologic history: New Mexico Geologic Society Special Publication 11, p. 389–406.

Mackey, G.N., III, 2009, Provenance of the South Texas Paleocene-Eocene Wilcox Group, western Gulf of Mexico basin: Insights from sandstone modal compositions and detrital zircon chronology [M.S. Thesis]: Austin, Texas, University of Texas at Austin, 153 p.

McBride, E.F., Land, L.S., Diggs, T.N., and Mack, L.E., 1988, Petrography, stable isotope geochemistry and diagenesis of Miocene sandstones, Vermillion block 31, offshore Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 38, p. 513–523.

McDowell, F.W., 2007, Geologic transect across the northern Sierra Madre Occidental volcanic field, Chihuahua and Sonora, Mexico: Geological Society of America Digital Map and Chart Series 6, 70 p.

McMillan, M.E., Angevine, C.L., and Heller, P.L., 2002, Postdepositional tilt of the Miocene-Pliocene Ogallala Group on the western Great Plains: Evidence of late Cenozoic uplift of the Rocky Mountains: Geology, v. 30, p. 63–66, doi: 10.1130/0091-7613(2002)030<0063:PTOTMP>2.0.CO;2.

McMillan, M.E., Heller, P.L., and Wing, S.L., 2006, History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau: Geological Society of America Bulletin, v. 118, p. 393–405, doi: 10.1130/B25712.1.

Milner, M.K., Johnson, C., and Bereskin, S.R., 2005, Interpretation of the Paleocene-Eocene sequence boundary, northwest San Juan Basin, New Mexico: The Mountain Geologist, v. 42, p. 11–22.

Molnar, P., 2004, Late Cenozoic increase in accumulation rates of terrestrial sediment: How might climate change have affected erosion rates?: Annual Review of Earth and Planetary Sciences, v. 32, p. 67–89, doi: 10.1146/annurev.earth.32.091003.143456.

Pazzaglia, F.J., and Brandon, M.T., 1996, Macrogeomorphic evolution of the post-Triassic Appalachian Mountains determined by deconvolution of the offshore basin sedimentary record: Basin Research, v. 8, p. 255–278, doi: 10.1046/j.1365-2117.1996.00274.x.

Pazzaglia, F.J., and Kelley, S.A., 1998, Large-scale geomorphology and fission-track thermochronology in topographic and exhumation reconstructions of the Southern Rocky Mountains: Rocky Mountain Geology, v. 33, p. 229–257.

Perkins, M.E., and Nash, B.P., 2002, Explosive silicic volcanism of the Yellowstone hotspot: The ash fall tuff record: Geological Society of America Bulletin, v. 114, p. 367–381, doi: 10.1130/0016-7606(2002)114<0367:ESVOTY>2.0.CO;2.

Poag, C.W., and Sevon, W.D., 1989, A record of Appalachian denudation in postrift Mesozoic and Cenozoic sedimentary deposits of the U.S. Middle Atlantic continental margin: Geomorphology, v. 2, p. 119–157, doi: 10.1016/0169-555X(89)90009-3.

Potter, P.E., and Szatmari, P., 2009, Global Miocene tectonics and the modern world: Earth-Science Reviews, v. 96, p. 280–295, doi: 10.1016/j.earscirev.2009.07.003.

Radovich, B.J., Moon, J., Connors, C.D., and Bird, D.E., 2007, Insights into structure and stratigraphy of the northern Gulf of Mexico from 2D pre-stack depth migration imaging of mega-regional onshore to deep water, long-offset seismic data: Gulf Coast Association of Geological Societies Transactions, v. 57, p. 633–637.

Raynolds, R.G., 2002, Upper Cretaceous and Tertiary stratigraphy of the Denver Basin, Colorado: Rocky Mountain Geology, v. 37, p. 111–134.

Retallack, G.J., 1997, Neogene expansion of the North American prairie: Palaios, v. 12, p. 380–390, doi: 10.2307/3515337.

Rittenour, T.M., Blum, M.D., and Goble, R.J., 2007, Fluvial evolution of the lower Mississippi River valley during the last 100 k.y. glacial cycle: Response to glaciations and sea-level change: Geological Society of America Bulletin, v. 119, p. 586–608, doi: 10.1130/B25934.1.

Saucier, R.T., 1994, Geomorphology and Quaternary geologic history of the Lower Mississippi Valley: Vicksburg, Mississippi, U.S. Army corps of Engineers Waterways Experiment Station, 364 p.

Scott, G.R., 1975, Cenozoic surfaces and deposits in the southern Rocky Mountains, *in* Curtis, F.B., ed., Cenozoic history of the southern Rocky Mountains: Boulder, Colorado, Geological Society of America Memoir 144, p. 227–248.

Scott, G.R., 1982, Paleovalley and geologic map of northeastern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map 1–1378, 12 p.

Seager, W.R., Mack, G.H., and Lawton, T.F., 1997, Structural kinematics and depositional history of a Laramide uplift-basin pair in southern New Mexico: Implications for development of intraforeland basins: Geological Society of America Bulletin, v. 109, p. 1389–1401, doi: 10.1130/0016-7606(1997)109<1389:SKADHO>2.3.CO;2.

Seni, S.J., 1980, Sand-body geometry and depositional systems, Ogallala Formation, Texas: Texas Bureau of Economic Geology Report of Investigations No. 105, 36 p.

Sewall, J.O., and Sloan, L.C., 2006, Come a little bit closer: A high-resolution climate study of the early Paleogene Laramide foreland: Geology, v. 34, p. 81–84, doi: 10.1130/G22177.1.

Smith, L.N., 1992, Stratigraphy, sediment dispersal and paleogeography of the Lower Eocene San Jose Formation, San Juan Basin, New Mexico and Colorado, *in* San Juan Basin IV: New Mexico Geological Society Guidebook, 43rd Field Conference, p. 297–309.

Smith, L.N., Lucas, S.G., and Elston, W.E., 1985, Paleogene stratigraphy, sedimentation and volcanism of New Mexico, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of west-central United States: Denver, Colorado, Rocky Mountain Section SEPM, p. 293–315.

Smith, M.E., Carroll, A.R., and Singer, B.S., 2008, Synoptic reconstruction of a major ancient lake system: Eocene Green River Formation, western United States: Geological Society of America Bulletin, v. 120, p. 54–84, doi: 10.1130/B26073.1.

Sømme, T.E., Helland-Hansen, W., Martinsen, O.J., and Thurmond, J.B., 2009, Relationships between morphological and sedimentological parameters in source-to-sink systems: A basis for predicting semiquantitative characteristics in subsurface systems: Basin Research, v. 21, p. 361–387, doi: 10.1111/j.1365-2117.2009.00397.x.

Steven, T.A., Evanoff, E., and Yuhas, R.H., 1997, Middle and late Cenozoic tectonic and geomorphic development of the Front Range of Colorado, *in* Colorado Front Range Guidebook: Rocky Mountain Association of Geologists, p. 115–123.

Syvitski, J.P.M., and Milliman, J.D., 2007, Geology, geography, and human battle for dominance over the delivery of fluvial sediment to the coastal ocean: The Journal of Geology, v. 115, p. 1–19, doi: 10.1086/509246.

Thompson, R.S., 1991, Pliocene environments and climates in the western United States: Quaternary Science Reviews, v. 10, p. 115–132, doi: 10.1016/0277-3791(91)90013-K.

Thorne, J.A., and Swift, D.J.P., 1991, Sedimentation on continental margins, VI: A regime model for depositional sequences, their component systems tracts, and bounding surfaces, *in* Swift, D.J.P., Oerten, G.F., Tillman, R.W., and Thorne, J.A., eds., Shelf sand and sandstone bodies: Oxford, International Association of Sedimentologists Special Publication Number 14, p. 189–255.

Tweto, O., 1975, Laramide (late Cretaceous-early Tertiary) orogeny in the southern Rocky Mountains, *in* Curtis, F.B., ed., Cenozoic history of the southern Rocky Mountains: Boulder, Colorado, Geological Society of America Memoir 144, p. 1–44.

USGS, 2003, North America Tapestry of Time and Terrain: Geological Investigations Series I-2781, Version 1.0.

Weissmann, G.S., Hartley, A.J., Nichols, G.J., Scuderi, L.A., Olson, M., Buehler, H., and Banteah, R., 2010, Fluvial form in modern continental sedimentary basins: Distributive fluvial systems: Geology, v. 38, p. 39–42, doi: 10.1130/G30242.1.

Wilf, P., 2000, Late Paleocene-early Eocene climate changes in southwestern Wyoming: Paleobotanical analysis: Geological Society of America Bulletin, v. 112, p. 292–307, doi: 10.1130/0016-7606(2000)112<292:LPECCI>2.0.CO;2.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to present: Science, v. 292, p. 686–693, doi: 10.1126/science.1059412.

Zachos, J.C., Dickens, G.R., and Zeebe, R.E., 2008, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics: Nature, v. 451, p. 279–283, doi: 10.1038/nature06588.

Zarra, L., 2007, Chronostratigraphic framework for the Wilcox Formation (upper Paleocene-Lower Eocene) in the deep-water Gulf of Mexico: Biostratigraphy, sequences, and depositional systems, *in* Kennen, L., Pindell, J., and Rosen, N.C., eds., The Paleogene of the Gulf of Mexico and Caribbean basins: Processes, events, and petroleum systems: Gulf Coast Section SEPM 27th Annual GCSSEPM Foundation Bob F. Perkins Research Conference Proceedings, p. 81–145.