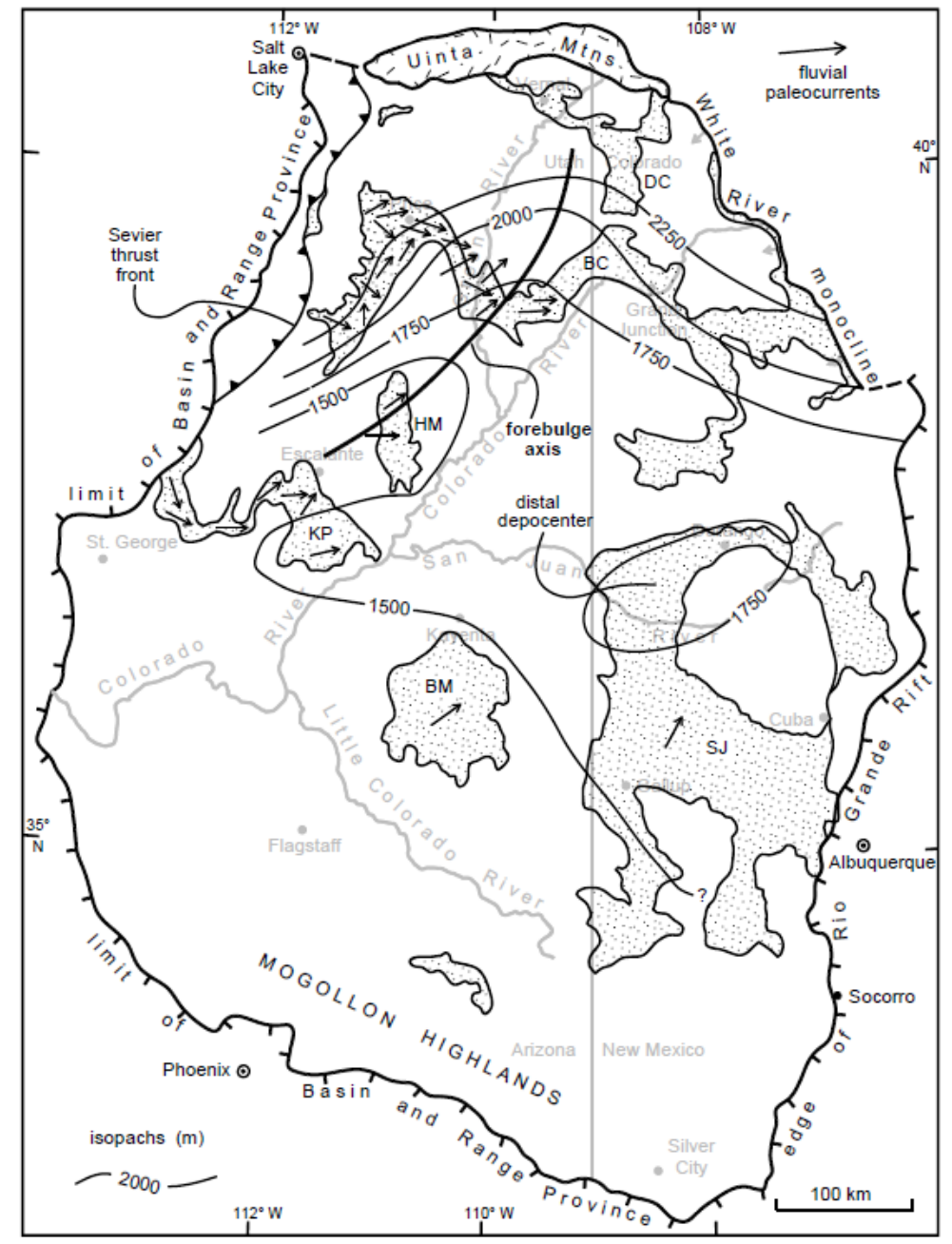
Notes on the Cretaceous and Laramide of the Colorado Plateau

William R. Dickinson, Univ. of Arizona



May 2018

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Arizona Geological Survey

Phil A. Pearthree, Director

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Cover: Outcrop belt (stippled) and reconstructed isopachs of pre-Maastrichtian (pre-Laramide) Upper Cretaceous strata forming the Mancos-Mesaverde deposystem on the Colorado Plateau (Mancos Shale, Mesaverde Group, and equivalent strata). Note that the isopach spacing is arithmetic, unlike the geometric spacing of isopachs on other paleogeographic maps, and that long segments of isopach lines are inferred from thicknesses recorded only round the periphery of the Colorado Plateau (BC–Book Cliffs, BM–Black Mesa, DC–Douglas Creek arch, HM– Henry Mountains, KP–Kaiparowits Plateau, SJ–San Juan basin). Paleocurrents are plotted only for fluvial and luviodeltaic strata, and not for equivalent marine strata exposed to the east and northeast.

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ARIZONA GEOLOGICAL SURVEY AZGS

Notes on the Cretaceous and Laramide of the Colorado Plateau

by

William R. Dickinson

University of Arizona

2018

Introduction by Jon Spencer, 2018

William R. Dickinson was in the process of preparing a comprehensive publication on the Mesozoic stratigraphy and tectonic setting of the Colorado Plateau when he died abruptly while on a geoarchaeological expedition to Tonga (Spencer, 2016). The book was largely written and the completed chapters were published posthumously by the Geological Society of America (Dickinson, 2018). Dickinson had drafted figures and written figure captions and some text for three additional chapters that were not included in GSA Special Paper 533. The topics of those three chapters are as follows:

Lower Cretaceous Cedar Mountain – Burro Canyon deposystem

Upper Cretaceous Mancos – Mesaverde deposystem

Laramide orogeny

The preliminary text and drafted figures for these uncompleted chapters are included in this Contributed Report which is made available by the Arizona Geological Survey in the hope that it might be useful to those researching the Cretaceous and Laramide geology of the Colorado Plateau.

References cited

Dickinson, W.R., 2018, Tectonosedimentary relations of Pennsylvanian to Jurassic strata on the Colorado Plateau: Geological Society of America Special Paper 533, 184 p., https://dx.doi.org/10.1130/2018.2533.

Spencer, J.E., 2016, William R. Dickinson, 1931-2015: National Academy of Sciences Biographical Memoir, 17 p. (http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/dickinson-william.pdf).

W.R. Dickinson, unpublished notes on Early Cretaceous of the Colorado Plateau

Compiled by J. Spencer, 2018

Thrust Onset: Early Cretaceous Cedar-Burro

The fluvial Cedar-Burro deposystem of the Colorado Plateau includes Lower Cretaceous strata and basal Upper Cretaceous strata assigned to the Cedar Mountain Formation west of the Colorado River and to the Burro Canyon Formation east of the Colorado River (Craig and Shawe, 1975; Tschudy et al., 1984; Aubrey, 1998). Cedar-Burro strata are lithologocally heterogeneous and display multiple intraformational scour surfaces indicative of condensed stratigraphy (Kirkland and Madsen, 1997). As a whole, however, the Cedar-Burro interval represents an integrated tectonosedimentary packet resting unconformably upon the fluvial Morrison deposystem and overlain disconformably by the mid-Cretaceous Dakota Sandstone of marine to marginal marine origin at the base of the Upper Cretaceous Mancos-Mesaverde deposystem. From lack of marine fossils, the age of the Cedar-Burro deposystem has been a challenge to specify in detail, but the best current opinion assigns its base to the Lower Cretaceous Barremian stage, allowing for a hiatus of ~15 myr between Morrison and Cedar-Burro sedimentation (Figs. 5-6). Northward drift of the Colorado Plateau was arrested between Morrison and Cedar-Burro time (Fig. 12), and Cedar-Burro paleolatitude was ~5º lower than maximum Morrison paleolatitudes (Figs. 90, 98). The minor adjustment in paleolatitude did not, however, have alter the general position of the Cedar-Burro deposystem in the rain shadow of the Cordilleran orogen.

Sevier thrusting in Utah initiated Cedar-Burro sedimentation (Lawton, 1985; Heller et al., 1986; Yingling and Heller, 1982). The Sevier segment of the retroarc Cordilleran thrustbelt may

well have been the youngest to activate, with a record of older thrusting farther north along the Cordilleran margin (Miall, 2009). Earlier precursor thrusting in the hinterland to the west of the Sevier thrustbelt is also not precluded by delayed initiation of deformation along the thrust front (DeCelles, 2004). The Cedar Mountain Formation thickens markedly westward, from ~50 m to 250+ m, from the Colorado River on the east into a foredeep along the Sevier thrust front to the west (Fig. 99). Fluvial paleocurrents are largely longitudinal toward the northeast within the Cedar Mountain Formation of the Sevier foredeep, but diverge to northwesterly and then to more easterly azimuths within the Burro Canyon Formation, which is only ~50 m thick over a wide area farther to the east (Fig. 99). The contrast suggests that the Burro Canyon Formation was deposited atop and beyond the foreland forebulge (Fig. 8) of the Sevier thrust system. The lateral transition from Cedar Mountain Formation to Burro Canyon Formation at the Colorado River is merely a convenient arbitrary stratigraphic convention, but approximates a fundamental tectonic transition from foredeep to forebulge for Lower Cretaceous strata deposited in the Sevier foreland (Stikes, 2007).

Cedar Mountain strata inferred here to be sourced largely within the Sevier thrustbelt to the west grade eastward across depositional strike, not down depositional dip, into Burro Canyon strata inferred here to be sourced largely from the Mogollon Highlands, the rift shoulder (Fig. 10) of the Bisbee basin to the south (Fig. 87). The greater percentage of sandstone in the Burro Canyon Formation than in the Cedar Mountain Formation reinforces the interpretation that the two correlative stratal units had different sources, for detritus from the Sevier thrustbelt would be expected to become finer grained with distance from the thrustbelt. The Cedar-Burro deposystem is truncated unconformably to the southwest (Peterson et al., 1980; Owen et al. 2005) by overlap

of the mid-Cretaceous Dakota Sandstone deposited as expanding Late Cretaceous transgression progressively overtopped the Mogollon Highlands.

Age Control

Buckhorn Equivalents

Facies Pattern

Dakota Contact

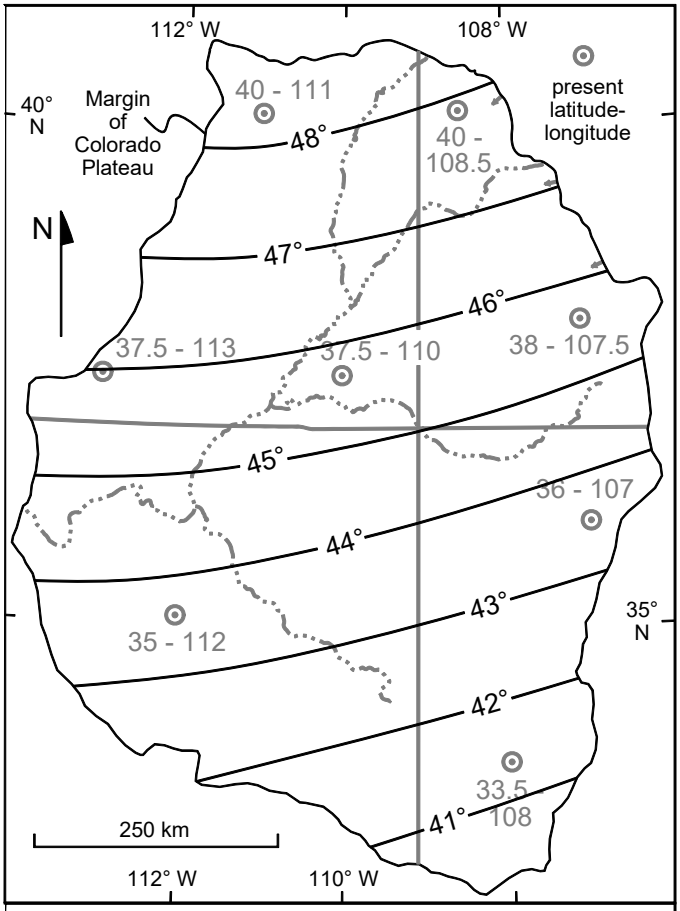
Provenance Relations

Figure L1. Inferred paleolatitudes of the Colorado Plateau during mid-Cretaceous sedimentation (Cedar-Burro deposystem, as well as Dakota Sandstone and Mancos Shale of the Mancos-Mesaverde deposystem). See Appendix 1 for paleomagnetic control. [98]

Figure L2. Areal distribution (stippled), thickness (isopachs), and sediment dispersal (paleocurrents) of the Lower Cretaceous Cedar-Burro deposystem (Cedar Mountain and Burro Canyon Formations and inferred equivalents). The Jackpile Sandstone Member of Morrison Formation (Owen et al., 1984) is treated as equivalent to the Burro Canyon Formation after Aubrey (1992) and Dickinson and Gehrels (2008b). See Appendices 2-4 for references. [99]

Figure L3. Comparison of detrital-zircon populations in sublitharenites of the Morrison deposystem (bottom curve) and in the Cedar Mountain (western phase) and Burro Canyon (eastern phase including the Jackpile Sandstone) Formatons of the Cedar-Burro deposystem on the Colorado Plateau. N is the number of samples and n is the number of zircon grains. Data from Dickinson and Gehrels (2008b), Ludvigson et al. (2010), and Hunt et al. (2011).

Figure L4. Chronostratigraphic framework of the Cedar Mountain Formation (western phase of the Cedar-Burro deposystem) on the Colorado Plateau (intraformational hiatuses not shown) adapted after Cifelli et al. (1997), Kirkland et al. (1997, 1998, 1999), Kirkland and Madsen (2007), Stikes (2007), Ludvigson et al. (2010, 2015), and Sprinkel et al. (2012) with stage boundaries adjusted to the timescale of Ogg and Hinnov (2012) and Walker et al. (2012). Uncertainties in stage boundaries at 2σ (0.2-0.8 myr; mean 0.5±0.2 myr) are not plotted for reasons of scale. The most proximal facies of the upper Cedar Mountain Formation exposed within the Sevier thrustbelt was denoted as San Pitch Formation (not shown) by Sprinkel et al. (1999). Palynomorphs from the Burro Canyon Formation (eastern phase of the Cedar-Burro deposystem) document a dominantly Aptian to Albian age (Tschudy et al. (1984).



mid-Cretaceous "stillstand" pole (130 - 90 Ma)

Fig. L1

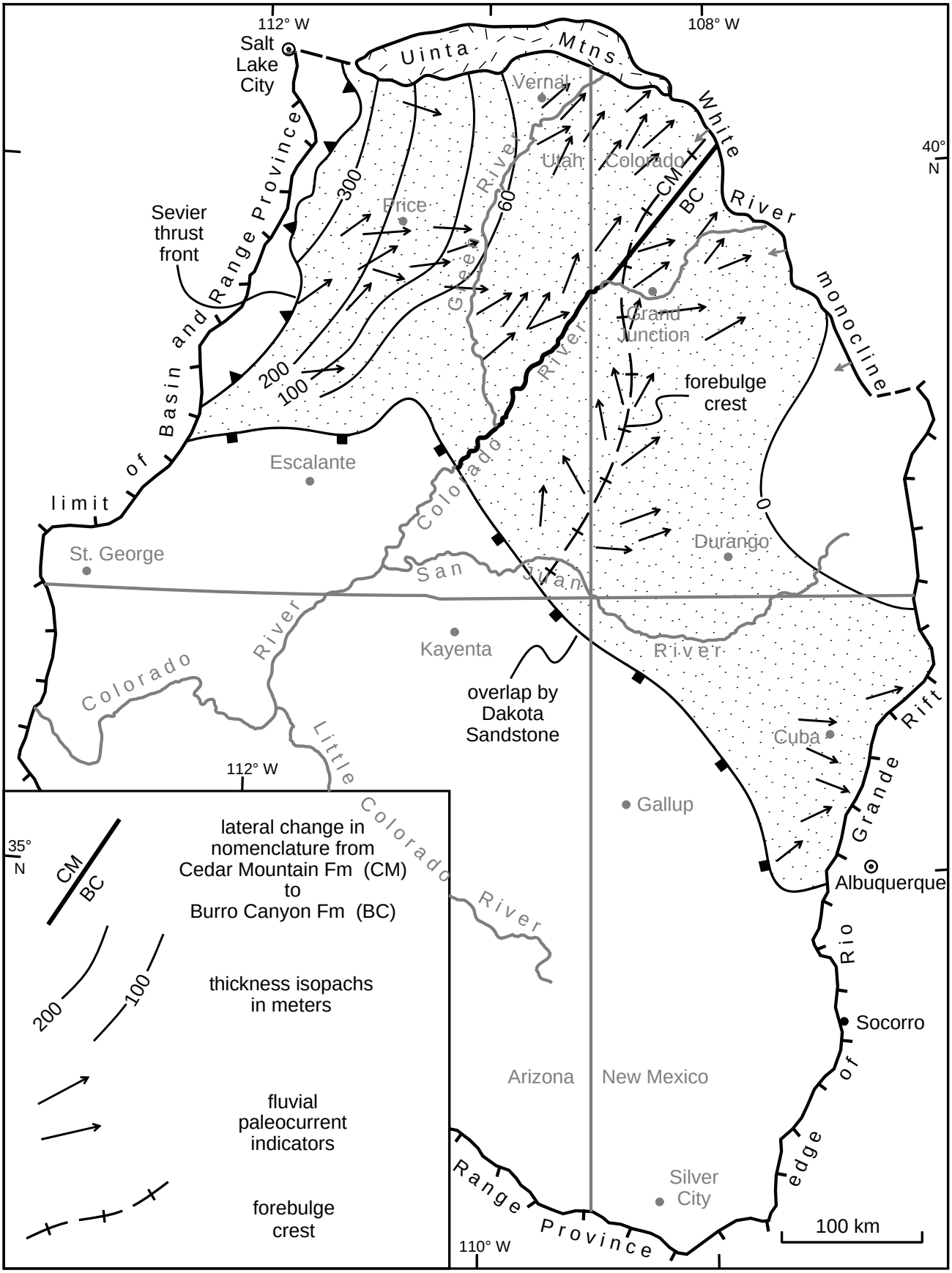

112° W
108° W
Salt Lake City
Uinta Mtns
Vernal
White River monocline
40° N
Utah
Colorado
CM
BC
Price
Sevier thrust front
Green River
Grand Junction
forebulge crest
limit of Basin and Range Province
300
200
100
60
0
Escalante
Colorado River
St. George
San Juan River
Durango
Kayenta
overlap by Dakota Sandstone
Cuba
Rio Grande Rift
Little Colorado River
Gallup
Albuquerque
Socorro
Arizona
New Mexico
Silver City
Range Province
edge of
110° W
100 km
35° N
lateral change in nomenclature from Cedar Mountain Fm (CM) to Burro Canyon Fm (BC)
thickness isopachs in meters
fluvial paleocurrent indicators
forebulge crest

Fig. L2

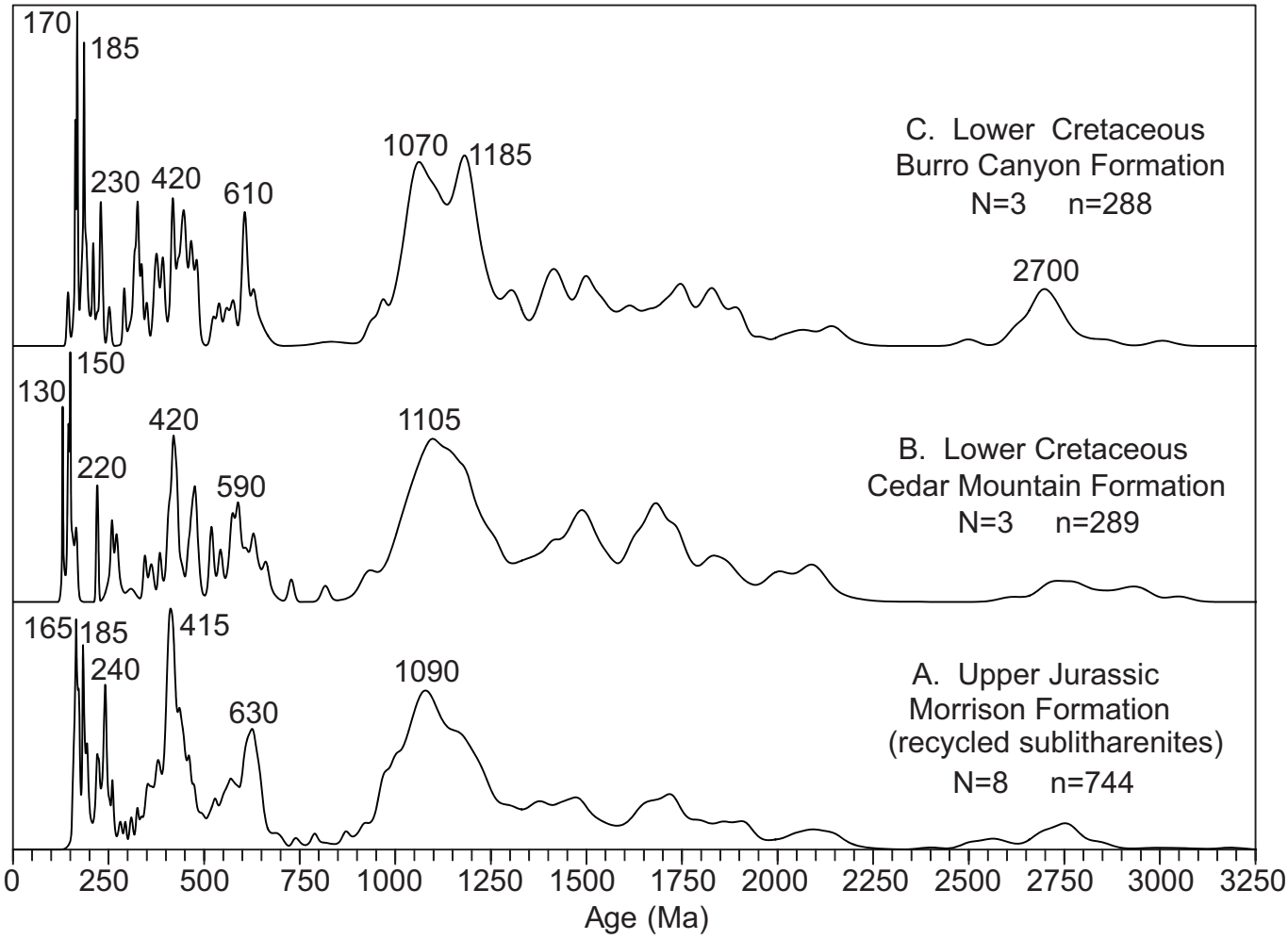

170
185
230
420
610
1070
1185
2700
C. Lower Cretaceous
Burro Canyon Formation
N=3 n=288
130
150
220
420
590
1105
B. Lower Cretaceous
Cedar Mountain Formation
N=3 n=289
165
185
240
415
630
1090
A. Upper Jurassic
Morrison Formation
(recycled sublitharenites)
N=8 n=744
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
Age (Ma)

Fig. L3

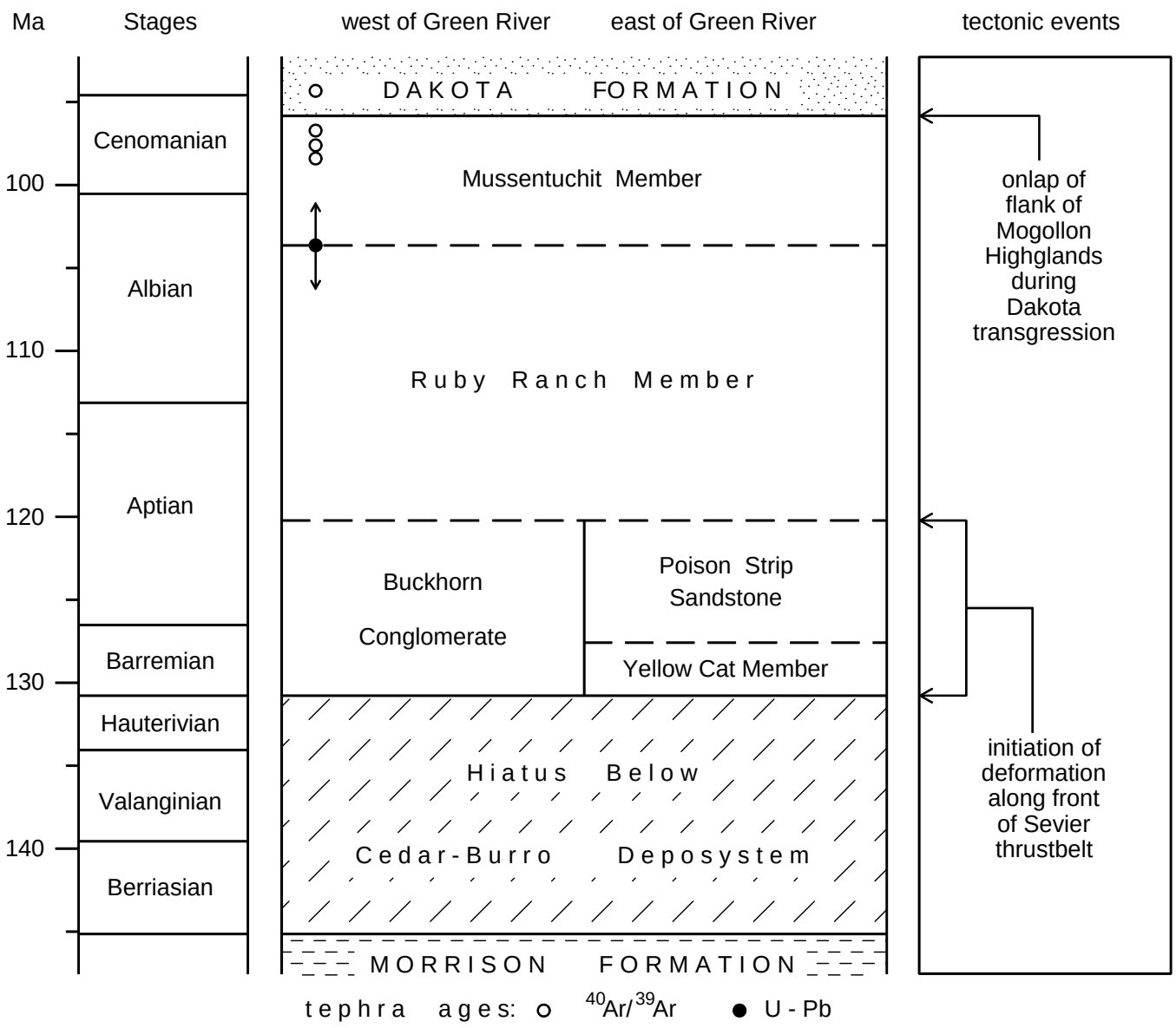

Ma
Stages
west of Green River
east of Green River
tectonic events
DAKOTA FORMATION
Cenomanian
100
Mussentuchit Member
Albian
110
Ruby Ranch Member
Aptian
120
Buckhorn
Conglomerate
Poison Strip
Sandstone
Barremian
130
Yellow Cat Member
Hauterivian
Hiatus Below
Valanginian
140
Cedar-Burro Deposystem
Berriasian
MORRISON FORMATION
onlap of flank of Mogollon Highglands during Dakota transgression
initiation of deformation along front of Sevier thrustbelt
tephra ages: ○ 40Ar/39Ar ● U-Pb

Fig. L4

text for Morrison is superseded by GSA Spec Paper 533.
Cedar Mountain - Burro Canyon text here was written in 2006

Morrison (and Cedar Mountain/Burro Canyon) Deposystem

Deposition of the Upper Jurassic Morrison Formation and similar fluvial facies in the overlying Lower Cretaceous Cedar Mountain and Burro Canyon Formations spanned the time interval during which the Colorado Plateau moved northward by continental drift into the belt of westerly winds (Anderson and Lucas, 1994b, 1996b), and the site of the plateau became a retroarc foreland basin, bounded to the west by the Sevier thrustbelt (DeCelles, 2004)and to the south by the Mogollon Highlands forming the rift shoulder of the Bisbee basin. The Bisbee rift had formed by Kimmeridgian time near the onset of Morrison sedimentation (Dickinson and Lawton, 2001), and thrusting along the Sevier belt was underway by Aptian (DeCelles et al., 1995) to Albian (Heller et al., 1986) time coincident with Cedar Mountain and Burro Canyon sedimentation. Drift of the Colorado Plateau northward out of the arid climatic zone is reflected by the character of Morrison paleosols, which imply a drier climate on the south than on the north, and record progressively more humid conditions through Morrison time (Demko et al., 2004).

The Morrison Formation includes a lower sand-rich interval represented by the Salt Wash and Westwater Canyon Members composed of fluvial channel sandstones and intercalated overbank mudstones, and an upper sand-poor interval represented by the Brushy Basin Member of variegated mudstone with minor sandstone lenses (Shawe et al., 1968; Cater, 1970; Petersen and Roylance, 1982; Peterson, 1984; Anderson and Lucas, 1995, 1997b, 1998; Lucas and Anderson, 1998; Currie, 1998).

Ar/Ar ages of ~155 Ma for three tuffs in the basal Tidwell Member (see below) fall near the Oxfordian-Kimmeridgian boundary (Kowallis et al, 1998). Overlying lower Morrison strata are not directly dated isotopically, but multiple K-Ar and Ar/Ar ages and a single U-Pb age for tuffs within the Brushy Basin Member range 150-145 Ma spanning Tithonian time (Kowallis et al., 1991, 1998; Currie, 1997; Greenhalgh et al., 2006), with an outlier age of 153 Ma (mid-Kimmeridgian) at Dinosaur National Monument (Kowallis et al., 1991). Palynomorphs and vertebrate fossils confirm that Morrison deposition did not begin before latest Oxfordian time and did not persist past Tithonian time (Lucas et al., 1985b; Litwin et al., 1998; Turner and Peterson, 1999). Lower Morrison Formation can be taken as Kimmeridgian in age and upper Morrison Formation as Tithonian in age. As the contact between the lower and the upper Morrison Formation is gradational and interfingering, the facies transition is probably time-transgressive in detail.

The age span of the overlying Cedar Mountain and Burro Canyon Formations is poorly constrained, but Aptian to Albian faunas are widespread (Tschudy et al., 1984; Currie, 1997; Lucas and Anderson, 1997a). Lower Cedar Mountain detrital zircons indicating a maximum (U-Pb) depositional age of ~125 Ma (Greenhalgh et al., 2006) near the Barremian-Aptian boundary, and upper Cedar Mountain ash dating (Ar/Ar) to 98 Ma (Cifelli et al., 1994) near the Albian-Cenomanian boundary, seemingly confirm an Aptian-Albian age span. An exclusively Aptian-Albian age implies a hiatus of ~20 million years between Morrison and Cedar Mountain-Burro Canyon deposition, or a series of condensed paleosols at horizons near the contact.

Woodward, 2001). An alternative explanation that preserves the notion of a large integrated lake basin is the supposition that the alkaline lake was intermittent or ephemeral in character, with fluvial deposits spread across the lake basin during times when infiltration temporarily soaked up surface waters (Turner and Fishman, 1991).

Regional facies relations and isopachs for the Brushy Basin Member, the underlying Salt Wash and Westwater Canyon Members, and the overlying Cedar Mountain and Burro Canyon Formations are difficult to reconcile, however, with the concept of a continuous integrated lake of subregional size during Brushy Basin deposition. As judged from the orientations of fluvial paleocurrents from channel sandstone bodies, the land surface sloped to the northeast or east across the full span of Brushy Basin deposition at the end of Salt Wash and Westwater Canyon deposition, and also at the onset of Cedar Mountain and Burro Canyon deposition. Unless water depth varied systematically, for which there is no evidence, the floor of any integrated lake would have been essentially flat, but the only way to build a flat lake floor on a sloping alluvial plain would be to onlap the alluvial plain westward, to produce thicker lake deposits toward the east. An analysis of clast sizes and reconstructed channel depths for the Buckhorn Conglomerate Member suggests a paleoslope of ~0.0016 (Heller et al., 2003), which would imply net relief of nearly 500 m across the 300+ km width of the Colorado Plateau. The Brushy Basin Member does not thicken systematically eastward, however, but instead forms a nearly uniform sediment blanket averaging ~110 m in thickness across the plateau, and can accordingly be viewed as representing a phase of dominantly fine sediment and ash sedimentation on an alluvial surface waterlogged locally to form multiple floodplain lakes. Statistically indistinguishable means of reported thicknesses for the Brushy Basin Member from inside and outside the inferred confines of Lake Too'dichi' are 107.5 ± 12.5 (95-120 m for n=12) and 112.5 ± 12.5 (100-125 m for n=10), respectively.

The eastward shift in the diagenetic facies of intercalated tuffs from clinoptilolite to analcime to albite might conceivably have been related to evolving hydrogeochemistry on and beneath the floodplain as surface and vadose water was modified by progressive evaporation and infiltration during sluggish flow eastward. Groundwater discharge from the alluvial plain into multiple alkaline wetlands (Dunagan and Turner, 2004) might thereby have promoted appropriate diagenetic conditions as effectively within local paludal to palustrine depositional environments as within a single large lake. The only way to have created and then extinguished a large lake basin would have been through the action of some enigmatic tectonic process that first formed a topographic depression by focused subsidence on the alluvial plain, and then recovered the initial slope of the alluvial plain by uplift of the same depression. This special pleading finds no ancillary support, either theoretical or empirical.

Cedar Mountain and Burro Canyon Formations

The correlative Cedar Mountain and Burro Canyon Formations are lithologically similar, with the name change made arbitrarily at the Colorado River (Tschudy et al., 1984; Aubrey, 1996, 1998). Both formations are composed entirely of intercalated fluvial

sandstone and mudstone representing channel and overbank deposits (Shawe et al., 1968; Cater, 1970; Aubrey, 1996; Currie, 1997), but the proportion of sandstone is greater in the Burro Canyon Formation than in the Cedar Mountain Formation, which is finer grained except for the basal Buckhorn Conglomerate Member with a maximum thickness of 20-30 m. The two units jointly form a sheetlike sediment blanket <75 m thick covering the Morrison Formation over most of the Colorado Plateau. Thicknesses range 40-60 m for the Burro Canyon Formation and 15-40 m for the Cedar Mountain Formation except where the latter thickens to 100-125 m on the north toward the Uinta Mountains and westward approaching the Sevier thrustbelt. The significance of variations in reported thickness are uncertain, but the contact with the Brushy Basin Member if the Morrison Formation vary stratigraphically. To the south and east, the Jackpile Sandstone (Owen, 1982), which is traditionally viewed as the uppermost unit of the Morrison Formation (Moench and Schlee, 1967; Condon and Huffman, 1984; Condon, 1989b; Anderson and Lucas, 1996b; Lucas and Anderson, 1998; Lucas and Woodward, 2001; Lucas and Heckert, 2003b), may instead be a local expression of the Burro Canyon Formation (Aubrey, 1992).

The contact of the Morrison Formation with the Lower Cretaceous fluvial units has long been difficult to establish or evaluate (Craig et al., 1955; Smith et al., 1963; Morris et al., 2003). Only where the basal Buckhorn Conglomerate Member (Currie, 1998) of the Cedar Mountain Formation, or the comparable Karla Kay Conglomerate Member (Ekren and Houser, 1965; O'Sullivan, 1997) of the Burro Canyon Formation, is present can the contact be readily delineated. Elsewhere, Morrison and Burro Canyon overbank strata are reported to intertongue locally, even though the contact is sharp where channel sands immediately overlie the contact (Simmons, 1957; Ekren and Houser, 1959; Shawe et al., 1968; Cater, 1970; Ridgley, 1977; O'Sullivan, 1997; Owen et al., 2005). Recent work has shown that coarse Buckhorn Conglomerate braided channels incised into the Morrison Formation are capped by a post-Buckhorn paleosol calcrete (Currie, 1998) in a relationship intimated by the presence of a ledgy paleosol capping variegated Morrison overbank deposits beneath the Burro Canyon Formation (Ekren and Houser, 1965) or overlying a sandstone-rich basal interval of the Burro Canyon Formation (Aubrey, 1998). The apparent hiatus of ~20 million years between Morrison and Cedar Mountain-Burro Canyon deposition calls special attention to the potential significance of the paleosol at the contact.

The Burro Canyon Formation apparently reflects dispersal of sediment to the north off the Mogollon Highlands forming the rift shoulder of the Bisbee basin, whereas finer grained strata of the Cedar Mountain Formation above the Buckhorn Conglomerate Member apparently reflect the initial spread of sediment beyond the Sevier foredeep across an evolving forebulge. The condensed or composite nature (Demko et al., 2004) of the paleosol horizon above the Morrison Formation may record development of a compound forebulge unconformity.

Despite the stratigraphic equivalence of the Cedar Mountain and Burro Canyon Formations (Lucas and Anderson, 1997a), as lateral components of the same fluvial complex, somewhat different paleocurrent trends suggest that sediment dispersal was

bivariant, with Cedar Mountain Formation derived mainly from the west and Burro Canyon Formation derived mainly from the south (Craig, 1981). Westward from the Colorado Plateau into the Sevier thrustbelt, the Cedar Mountain Formation oversteps the Morrison Formation to rest directly on the San Rafael Group (Lawton and Willis, 1987).

The contact of the Cedar Mesa and Burro Canyon Formations with the overlying Cenomanian (Tschudy et al., 1984) Dakota Formation is an erosional unconformity of regional extent (Cater, 1970), but the length of the pre-Dakota hiatus is uncertain areally. In detail, Dakota strata include both transgressive and regressive phases, but reflect the initial marine flooding of the retroarc basin. In the field, the most characteristic lithologic change across the contact is the prevalence of dark carbonaceous shale intervals between sandstone beds of the Dakota Formation, as opposed to nonmarine green mudstones below. Incision below the contact surface ranges up to 10-12 m above the Burro Canyon Formation (Ekren and Houser, 1965), and to 20 m above the Cedar Mountain Formation (Currie, 2002). The eastward pinchout of the Burro Canyon Formation in Colorado is probably the result of erosional overlap by the Dakota Formation (Tschudy et al., 1984). Both the Cedar Mountain and Burro Canyon Formations are overlapped on the southwest by the Dakota Formation (Peterson, et al., 1980; Owen et al., 2005), which farther to the southwest onlaps the flank of the Mogollon Highlands rift shoulder of the Bisbee basin.

CEDAR MOUNTAIN/BURRO CANYON FORMATION
Notes from 2006 files

Overview-Nomenclature

Simmons 1957: Burro Cyn Fm & Cedar Mtn Fm correlative with common fossils

Ekren & Houser 1959: named local Karla Kay conglomerate mem of Burro Cyn Fm (plus compensatory thicknesses)

Cater 1970: type Burro Cyn Fm is Burro Canyon near Slick Rock CO

Peterson et al 1980: Cedar Mtn Fm extends south to about Notom in central Utah

Craig, 1981: arbitrary boundary between Cedar Mtn Fm and Burro Cyn Fm along trend of Colorado River but Cedar Mtn from west and Burro Cyn from south

Tschudy et al 1984: CM/BC bdry along Colorado River, then projected NE to Grand Hogback east of Unita Mtns

Aubrey 1996: arbitrary boundary between Cedar Mtn & Burro Cyn Fms at Colorado R

Lawton & Willis 1987: Cedar Mtn directly overlies Summerville in Salina Canyon

O'Sullivan 1997: In McElmo Cyn, local Karla Kay Cg Mem Burro Cyn Fm analogous to Buckhorn Cg Mem Cedar Mtn Fm & lower Burro Cyn Fm interfingers with Brushy Basin Mem Morrison Fm [latter seems unlikely]

Lucas & Anderson 1997a: Cedar Mtn Fm & Burro Cyn Fm synonymous, so do not need the latter name

Heller et al 2003: Buckhorn slope is 0.0016 [~0.0015] (proximal in Utah) or ~300 m

Owen et al 2005: trough-xbedded sandy Burro Cyn Fm (with pebbles on internal scours and intercaltated greenish ms lenses ~ Brushy Basin) occurs below Dakota Ss marine and marginal marine in Chama basin (overlapped to SW beneath San Juan basin)

Currie 1997: Buckhorn Cg of Utah equates to Cloverly Cg of Wyo (but not to whole Cloverly Fm)

Age

Shawe et al 1968: On Dolores River Burro Cyn contains Early Cretaceous (probably Aptian) megafossils

Tschudy et al 1984: upper Cedar Mtn SE of Castledale is late Albian but lower Cedar Mtn may be equivalent to older Burro Cyn

Tschudy et al 1984: upper Burro Cyn SE of Slick Rock Aptian to early Albian and perhaps as old as Barremian (older part undated)

Cifelli et al 1994: upper Cedar Mtn ash Ar/Ar at 98.39±0.07 Ma [lower Cenomanian]

Lucas & Anderson 1997a: dinosaurs from lower Cedar Mtn [=Burro Cyn] of SE UT are Hauterivian-Barremian [by analogy only] but from upper Cedar Mtn are Aptian-Albian boundary

Currie 1997: Cedar Mtn Fm in central Utah Aptian-Albian (varied fossils)

Greenhalgh et al., 2006: DZ age (youngest U-Pb age peak) for lower Cedar Mtn Fm provides maximum depoage of 126±2.5 Ma (abstract) or 125.1±3.8 Ma (poster)

Lithology

Shawe et al 1968: On Dolores River Burro Cyn is interbedded fluvial ss-cg with thinner intercalated ms-sis intervals, and contains internal scours with reworked intrafm cg of Burro Cyn clasts

Cater 1970: Burro Cyn (fluvial) is gry-red xbed cgic ss with intercalated grn ms

Aubrey 1996: Cedar Mtn Fm is basal Buckhorn Cg Mem overlain by overbank ms with lenticular channel ss bodies, and Burro Cyn Fm is cgic fluvial channel ss and overbank ms (both scoured into Brushy Basin Mem of Morrison Fm)

Currie 1997: Cedar Mtn unconformable on Morrison, with Buckhorn Cg (degradational systems tract) at base within paleovalley and upper Cedar Mtn Fm (aggradational facies tract) over widespread paleosol developed on Brushy Basin Mem Morrison

Cedar Mountain – Burro Canyon contact with Dakota

Simmons 1957: Dakota (with carbonaceous sh) disconformable on Burro Cyn (with greenish sh)

Ekren & Houser 1965: Dakota scoured 10-12 m (local relief) into Burro Cyn (Ute Mtns)

Shawe et al 1968: contact best marked by carbonaceous shale in Dakota (plus or minus any basal cg because multiple cg layers on multiple scours occur with in Burro Cyn)

Cater 1970: erosional unconformity of regional extent below Dakota

Tschudy et al 1984: Dakota above CM/BC is palynologically early Cenomanian

Tschudy et al 1984: eastward pinchout limit of Burro Cyn probably erosional overlap of overlying Dakota

Currie 1997: Dakota unconformable on Cedar Mtn with incision up to 20 m

Currie 2002: Early Cretaceous foreland framework of forebulge and backbulge basin

Mancos - Mesaverde deposystem

Figure M1. Inferred paleolatitudes of the Colorado Plateau during Late Cretaceous sedimentation (Mesaverde Group of the Mancos-Mesaverde deposystem). See Appendix 1 for paleomagnetic control.

Figure M2. Outcrop belt (stippled) and reconstructed isopachs of pre-Maastrichtian (pre-Laramide) Upper Cretaceous strata forming the Mancos-Mesaverde deposystem on the Colorado Plateau (Mancos Shale, Mesaverde Group, and equivalent strata). Note that the isopach spacing is arithmetic, unlike the geometric spacing of isopachs on other paleogeographic maps, and that long segments of isopach lines are inferred from thicknesses recorded only around the periphery of the Colorado Plateau (BC–Book Cliffs, BM–Black Mesa, DC–Douglas Creek arch, HM–Henry Mountains, KP–Kaiparowits Plateau, SJ–San Juan basin). Paleocurrents are plotted only for fluvial and fluviodeltaic strata, and not for equivalent marine strata exposed to the east and northeast. See Appendices 2-4 for references.

Figure M3. Regional setting of the Cretaceous Cedar-Burro and Mancos-Mesaverde deposystems of the Colorado Plateau (shaded) at the southwestern corner of the Cordilleran foreland basin (stippled) near the tectonic syntaxis between the Sevier thrust belt and the Mogollon highlands. Geotectonic relations along the Cordilleran continental margin after Dickinson (2008, 2009, 2011, 2013b).

Figure M4. Sub-Dakota paleogeologic map (adapted after Dickinson, 2013a) showing progressive overlap of older Mesozoic deposystems of the Colorado Plateau (in *italics* after Figure B4) by the base of the Upper Cretaceous Mancos-Mesaverde deposystem along the tilted northern flank of the Mogollon highlands rift shoulder of the Bisbee rift basin in southern Arizona (Dickinson and Lawton, 2001b). Lower Cretaceous strata (bottom) onlapped the flank of the Mogollon highlands from the south (Lawton, 2004).

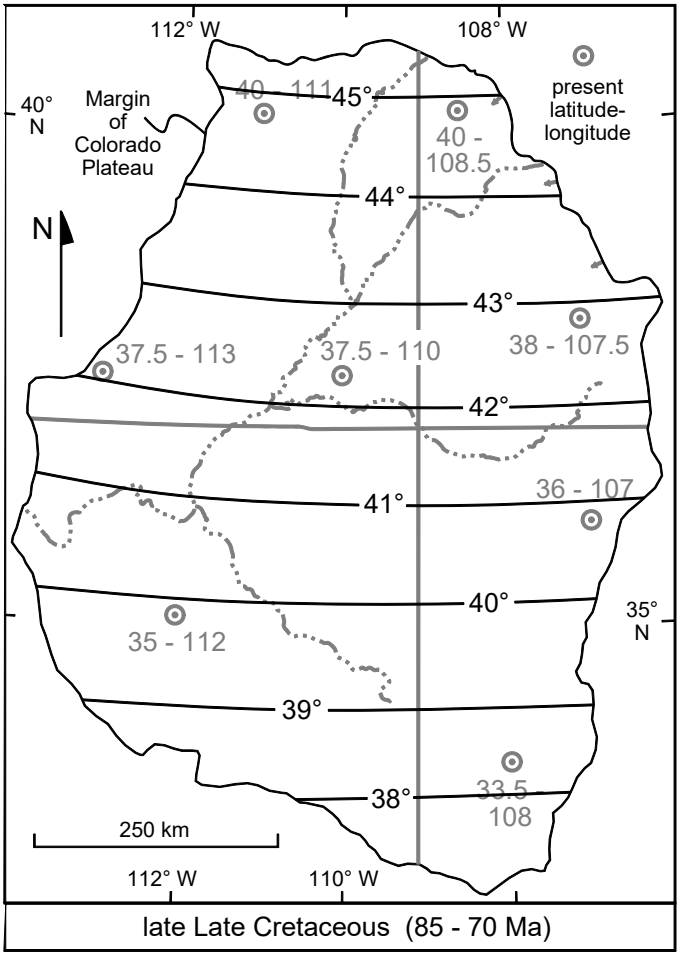

112° W
108° W
40° N
Margin of Colorado Plateau
40 - 111
45°
40 - 108.5
present latitude-longitude
44°
N
43°
37.5 - 113
37.5 - 110
38 - 107.5
42°
36 - 107
41°
40°
35° N
35 - 112
39°
38°
33.5 - 108
250 km
112° W
110° W
late Late Cretaceous (85 - 70 Ma)

Fig. M1

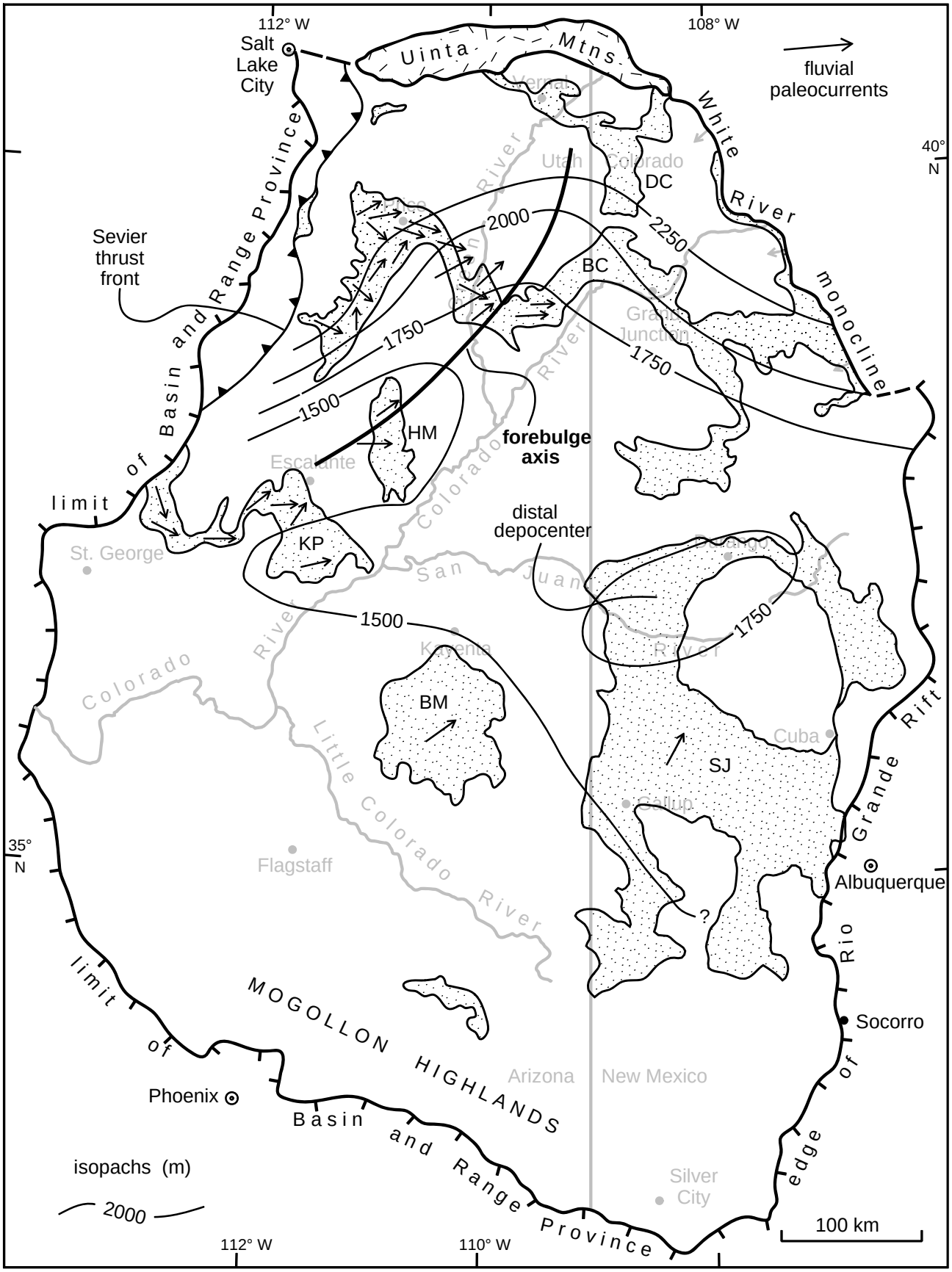

112° W
108° W
Salt Lake City
Uinta Mtns
fluvial paleocurrents
White River monocline
40° N
Utah
Colorado
DC
BC
2000
2250
1750
1500
Sevier thrust front
Basin and Range Province
limit of
HM
forebulge axis
Escalante
Colorado River
Grand Junction
distal depocenter
KP
St. George
San Juan River
Durango
Kayenta
BM
SJ
Cuba
Gallup
Grande Rift
Rio
Albuquerque
35° N
Flagstaff
Little Colorado River
?
Socorro
MOGOLLON HIGHLANDS
Arizona
New Mexico
Phoenix
edge of
Silver City
isopachs (m)
2000
100 km
112° W
110° W

Fig. M2

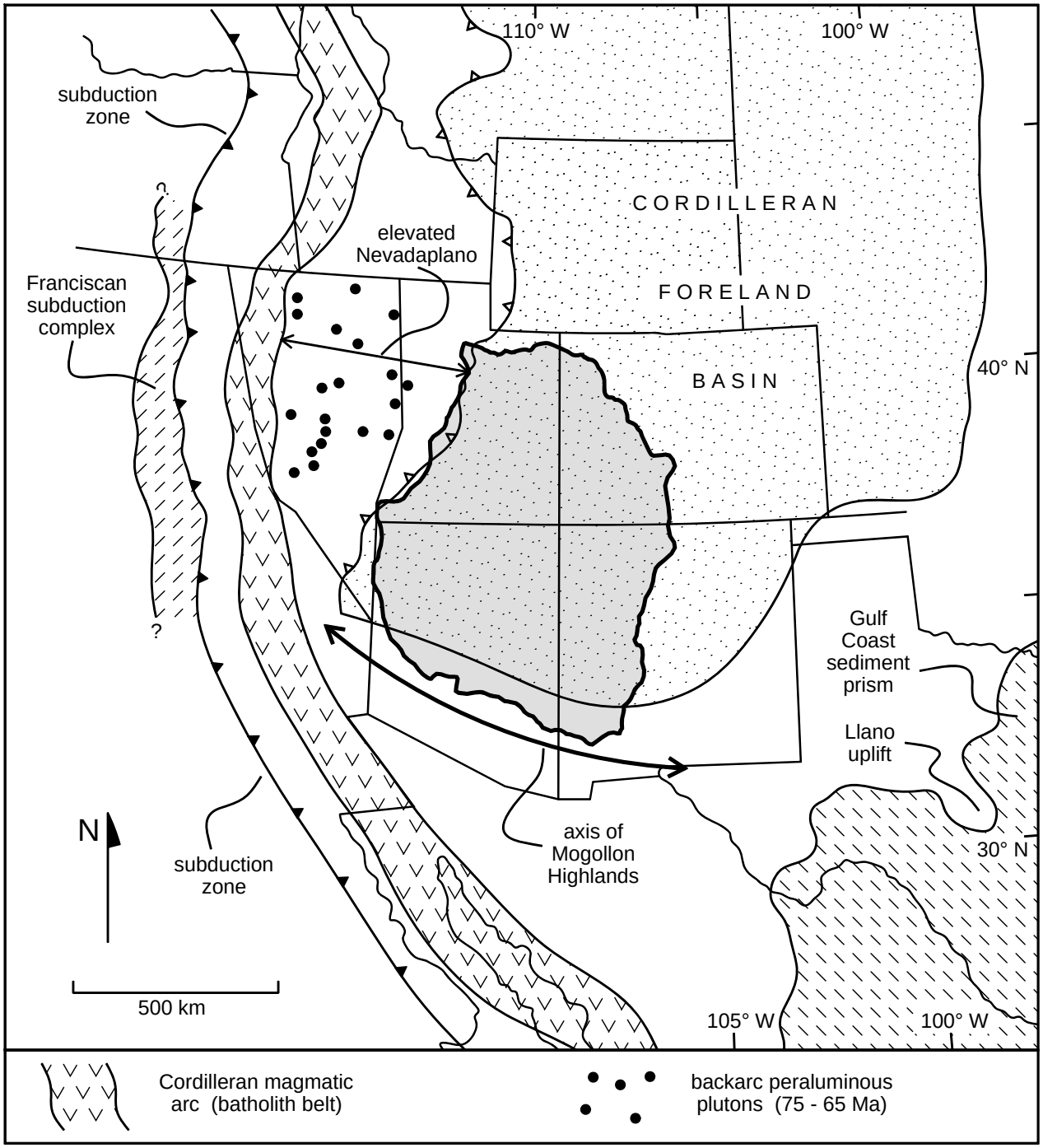

110° W
100° W
subduction
zone
CORDILLERAN
FORELAND
BASIN
elevated
Nevadaplano
Franciscan
subduction
complex
?
?
40° N
Gulf
Coast
sediment
prism
Llano
uplift
N
subduction
zone
axis of
Mogollon
Highlands
30° N
500 km
105° W
100° W
Cordilleran magmatic
arc (batholith belt)
backarc peraluminous
plutons (75 - 65 Ma)

Fig. M3

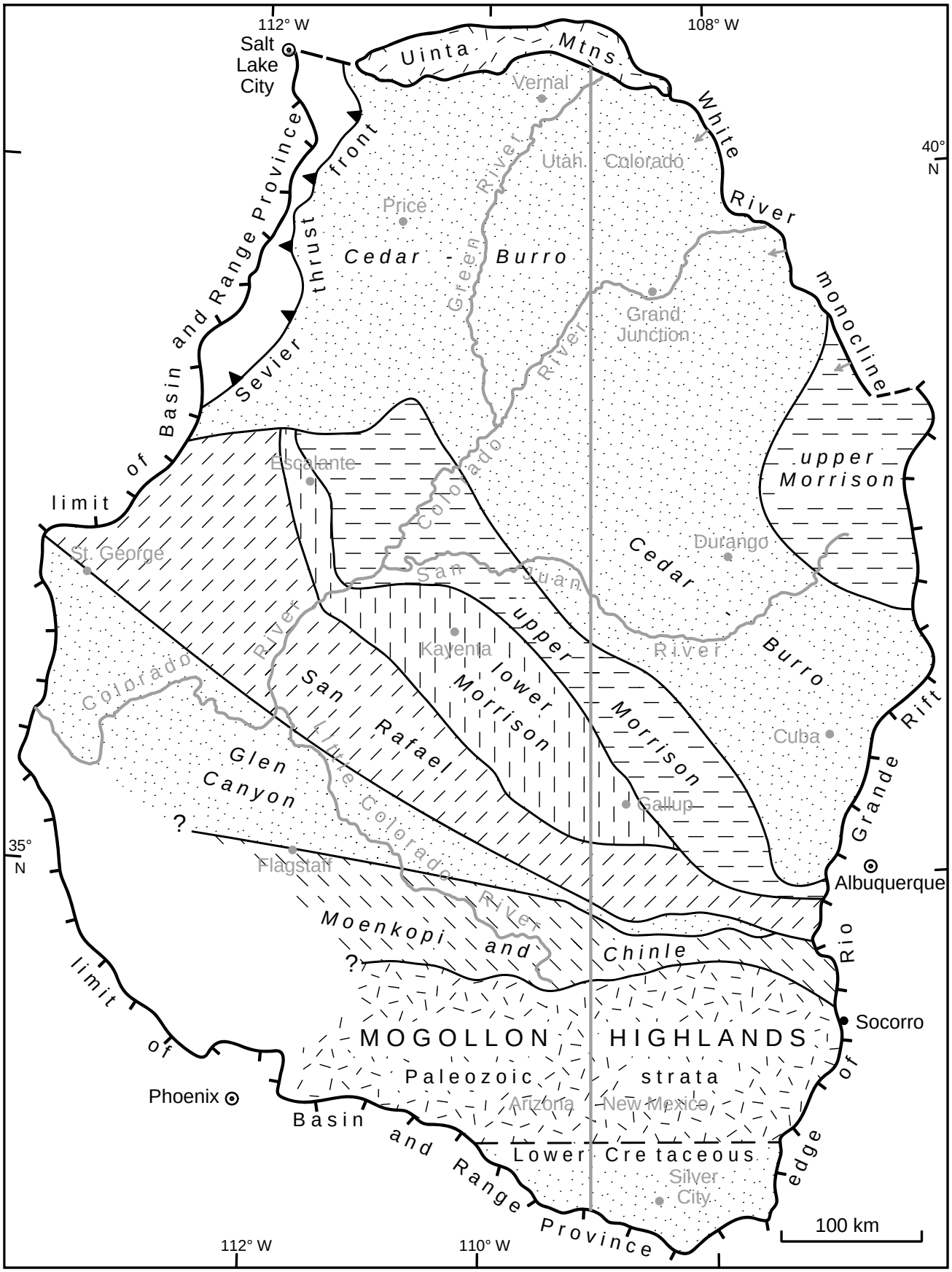


Fig. M4

note in files: "check re Burro Canyon above Mules Ear"

MANCOS SHALE–MESAVERDE GROUP
Notes from 2006 files

OverviewPaleoshorelines and Facies

Weimer 1960
Weimer 1970
Peterson and Kirk 1977
Peterson et al 1980
Cumella 1983
Fouch et al 1982
Fouch et al 1983
Molenaar 1977
Molenaar 1983
Ryer 1983
Ryer and McPhillips 1983
Nummedal & Molenaar 1995
DeCelles & Cavazza 1999 [Mesaverde megafans in both central & SW Utah]
Eaton & Nations 1991
Eaton 1991
DeCelles 2004

Plateau-Thrustbelt Correlations

Jefferson 1982: Indianola of Cedar Hills: (a) Sanpete Fm, 600 m cgic braided fluvial overlain by 75 m nearshore marine (675 m total); (b) Allen Valley Sh, 110 m dark sh & thn-bed ss; (c) Funk Valley Fm, 900 m intertonguing fluvial braidplain cgic ss and lagoonal-nearshore marine ss; (d) Sixmile Cyn Fm, 2180 m fluvial ss-cg (lower 850 m massive braidplain and alluvial fan ~ lower 630 m at type Sixmile Cyn; next 1200 m sandy fluvial facies ~ 500 m ss-sis at type Sixmile Cyn; 130 m alluvial fan facies just below North Horn unconformity ~ 210 m pebbly ss & cg at type Sixmile Cyn

Lawton 1982: Indianola lithofacies include intertonguing and laterally gradational alluvial fan cg, braided fluvial cg and cgic ss, meanderbelt fluvial ss-sis, delta distributary ss, lagoonal ss-sis-ms, delta front foreshore barrier & marine sheet ss), offshore marine sis-ms

Lawton 1982: Sanpete ~ Dakota [& Cedar Mtn], Allen Valley (middle Turonian) ~Tununk Mem Mancos, basal Funk Valley ~ Ferron, Funk Valley ~ Bluegate Mem Mancos, lower Sixmile ~ Emery-Masuk and Star Pt, middle Sixmile ~ Blackhawk, upper Sixmile ~ Castlegate-Price River

Fouch et al 1982, 1983: Sanpete ~ Dakota, Allen Valley ~ Mancos Tununk, Funk Valley (Turo-Coniac-Santon ~ Blue Gate, Sixmile ~ Emery-Star Pt-Blackhawk-Castlegate

Lawton 1983: Castlegate-Bluecastle paleocurrents SE off Sevier thrustbelt (transverse foreland), but Price River-Farrer-Tuscher paleocurrents NE parallel to Sevier thrustbelt (foreland longitudinal)

Lawton 1985: upper Albian palynos near cgic base of Indianola on Gunnison Plateau (equivalent to Cedar Mtn Fm); thickest Indianola Gp (Cedar Hills) is 3950 m

Lawton 1985: within Indianola Gp, 350-750 m Sanpete Fm (Alb-Ceno) ~ Dakota [+ Cedar Mtn], 75-200 m Allen Valley Sh (mid Turo) ~ Mancos Tununk, 750-950 m Funk Valley Fm (sandy Turo-Conia-Santon) ~ Mancos Ferron-Bluegate, 1200 m lower-middle Sixmile Cyn Fm (Santon-Camp) ~ Mancos Emery-Masuk and Star Pt-Blackhawk, 200+ m upper Sixmile Cyn Fm (Camp) ~ Castlegate-Price River

Lawton & Willis 1987: In Salina Cyn, Cedar Mtn Fm (formerly "Morrison?") is 260 m cg and variegated ms-sis, Sanpete Fm is 270 m of lower cg & upper tan ss-sis, Allen Valley Sh is 270 m gry ms-sh, Funk Valley Fm 260 m (eroded top) white-tan ss-sis

Ferron Sandstone Member of Mancos Shale (No-Cent UT)

Cotter 1971: Ferron Ss Mem of Mancos Sh includes good fluvio-deltaic channel facies

Cotter 1975: Ferron Ss Mem of Mancos Sh marine and marginal marine facies from longshore sediment transport (off Vernal delta to the north)

Peterson & Ryder 1975: Ferron Ss Mem conformable gradationally above Tununk Sh Mem but overlain unconformably [transgression] by Blue Gate Sh Mem with basal lag cg (~one foot thick)

Ryer 1981: Ferron Ss Mem of Mancos Sh includes deltaic coals

Matheny & Picard 1985: Emery Ss Mem of Mancos Sh only tidalite-shoreface-offshore

Ryer & Anderson 2004: Ferron Ss includes shelf ss, shoreface, foreshore, tidal inlet, bay-lagoon, mouthbar, distributary channel, and overbank facies

Edwards et al 2005: Emery Ss Mem of Mancos Sh only shoreface and offshore

Castlegate Sandstone of Mesaverde Group (No-Cent UT)

Van de Graaf 1972: Castlegate Ss a blanket fluvial braidplain of a regressive fluviodeltaic complex

Lawton 1986b: Late Campanian Castlegate Ss includes Bluecastle Tongue (above Neslen-Sego-Buck) with main part grading upward from sandy alluvial braidplain to meandering stream deposits (with Bluecastle similar to lower Castlegate a coarser coastal alluvial plain)

Lawton 1986b: Bluecastle Tongue still a blanket sheet from west, but Price River and Farrer longitudinal from SW with Tuscher partly reworked off San Rafael Swell in latest Campanian time

Eaton 1991: Castlegate is middle Campanian

Chan & Pfaff 1991: Castlegate an eastward prograding fluviodeltaic complex shed from Sevier thrustbelt with lower Castlegate in Price Cyn and Bluecastle Tongue both trough xbedded multistory sand bodies [braidplain] with upper Castlegate rippled lateral accretion deposits and overbanl ss-sis [crevasse spaly and floodplain]

Chan & Pfaff 1991: Lower Castlegate braidplain progradation from active thrusting, then transgression to trigger middle [upper main body] higher sinusosity streams, followed by renewed progradation for upper [Bluecastle Tongue], and streams transitioned from proximal braidplain to distal more sinuous streams

Miall 1993: Castlegate an amalgamation of braided-river sand sheets

Olsen et 1995: Castlegate Ss (Campanian) is trough xbedded & ripple lam ss, downstream accreting in lower part and laterally accreting in upper part

Giuseppe & Heller 1998: San Rafael Swell growing by Price River/Farrer time but not at Castlegate time (based on attenuation of Price River/Farrer over San Rafael Swell)

Robinson & Slingerland 1998: Castlegate deposition influenced by both tectonism and eustasy

McLaurin & Steel 2000: middle Castlegate (between main Castlegate and Bluecastle) of Buck Tongue-Sego-Neslen includes five transgress-regress estuarine infillings composed of fluvial-tidal distributary channel to interdistributary bay deposits

Miall & Arush 2001a, 2001b: intraformational unconformities in Castlegate Sandstone

Horton et 2004: Castlegate Ss progradation tied to active thrusting of Charleston-Nebo thrust sheet

Davies et al 2006: Blackhawk below Castlegate grades from delta plain (west) to delta front shoreface (east) beneath punctuating coal beds

Lynds & Hajek 2006: type lower Castlegate a braidplain with channels 1.5-8.5 m deep (average 4.1 m) ana tens to hundreds of meters wide

Henry/Kaiparowits Region (So-Cent UT)

Peterson 1969: four members of Straight Cliffs Fm are Tibbett Cyn (beach and shallow marine cliff-former gradational above Tropic Sh), Smoky Hollow (floodplain-lagoonal-paludal slope-former) capped by unconformity (Tibbett Cyn & Smoky Hollow middle to late Turon), John Henry (marine on NE to nonmarine on SW slope-former with much coal), Drip Tank (fluvial cliff-former) progradational (John Henry & Drip Tank middle Coniac to early Campan)

Peterson & Law 1980: Mancos Sh (Henry Mtns) includes late Ceno to middle Turon Tununk Sh Mem, grady overlying middle to upper Turon Ferron Ss Mem (lower part marginal marine but upper part estuarine to mouthbar fluvial channel sands and carbonaceous delta plain overbanks, unconformably overlying Santon Bluegate Sh Mem (Coniacian missing), lower Campanian "Emery" Ss Mem & Masuk Sh Mem (Henry Mtns "Emery" not correlatrive with type Emery)

Eaton 1991: Wahweap Formation is middle Campanian

am Ende 1991: Dakota is fluvial, lagoonal, estuarine, shoreface (topped by ravinement) of Cenomanian age

Shanley & McCabe 1991: Straight Cliffs Fm members over Tropic Sh (bottom to top): Tibbet Cyn mainly TST, Smoky Hollow mainly TST, John Henry HST, Driptank above sequence bdry progradatonal

Shanley & McCabe 1991: Driptank Mem Straight Cliffs Fm is best braided fluvial on Kaiparowits (John Henry Mem mostly shoreface)

Shanley & McCabe 1993, 1995: most progradational fluviodeltaic facies in upper Turonian Ferron Ss Mem of Mancos Sh and lower Campanian Driptank Mem of Straight Cliffs Fm [but latter too condensed and Wahweap Fm better]

Goldstrand 1990, 1992, 1994: Sediment sources both from thrustbelt and to southwest

Nichols 1997: Palynological ages of Markagunt-Kaiparowits units: Dakota, Cenomanian; lower Straight Cliffs, Turonian; upper Straight Cliffs, Coniacian or Santonian; type Kaiparowits, Campanian (not Maastrichtian) [so Wahweap OK as Campanian]

Fillmore 1993: Southern Sevier foreland (UT-NV-AZ corner) cgic debris from west early, then longitudinal feed to NE as foreland trough subsided

Lawton et al 2003: feldspatholithic sands (upper member of Wahweap Fm with trough xbedded multistory channel complexes) from SW & So, quartzolithic and quartzose sands (capping member of Wahweap Fm with amalgamated multistory channel complexes) from SW & W [try to collect both units if can find!]

Lawton et al 2003: Drip Tank mem of Straight Cliffs Fm amalgamated multistory sand bodies with trough and planar xbedding (condensed fluvial facies tract)

Black Mesa Basin

Page and Repenning 1958: Toreva includes lower ss transitional above Mancos Sh [shoreface], middle carby sis-ms-ss [delta plain], and upper trough xbedded ss [fluviodeltaic progradation] in a regressiuve succession

Eaton and Nations 1991: Toreva Formation is upper Turonian

San Juan Basin

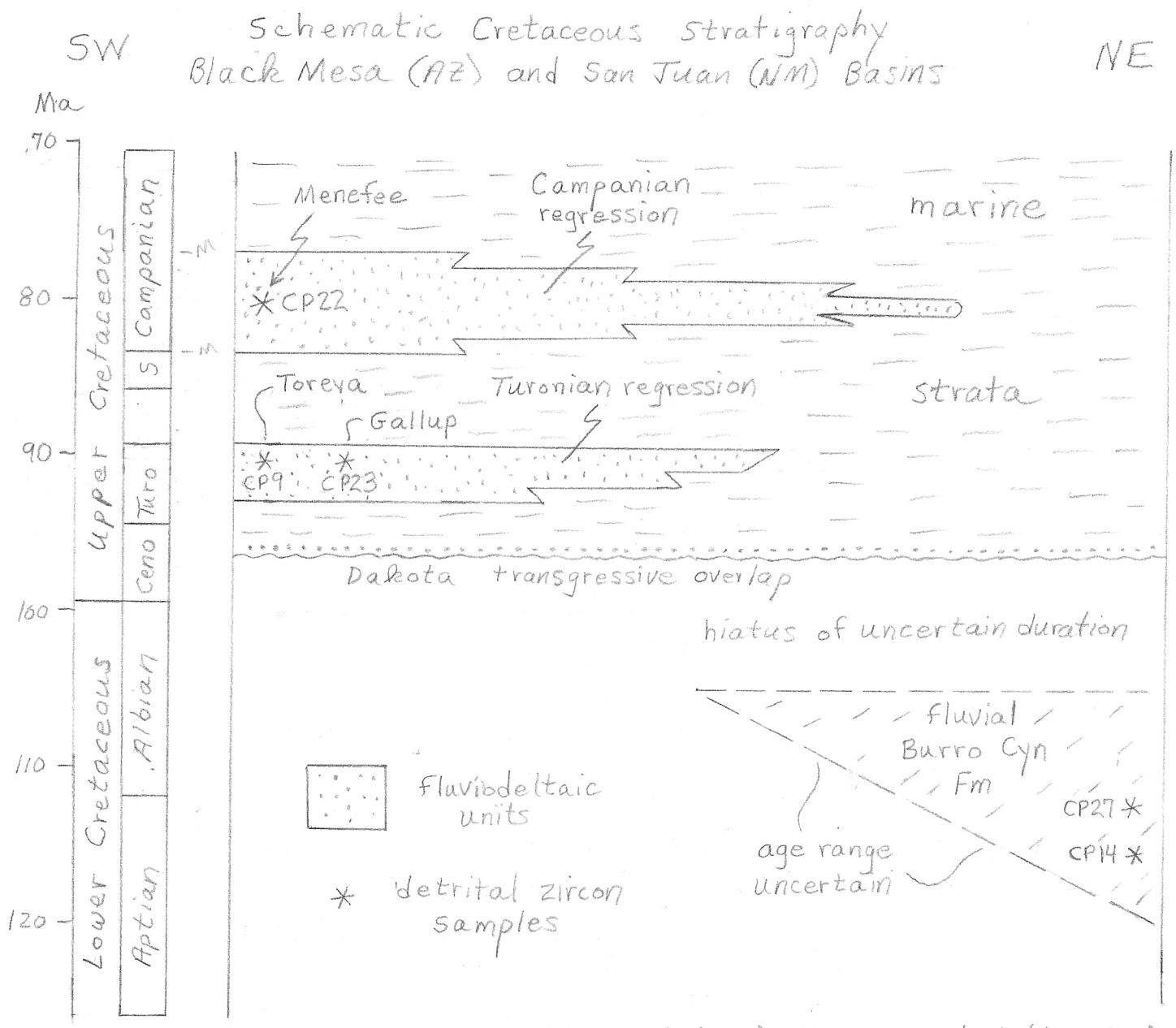
Wanek 1959: coal-bearing nonmarine Menefee Fm a NE-tapering wedge between marine Point Lookout Ss (regressive) below and Cliff House Ss (trnagressive) above

Eaton & Nations 1991: Gallup Sandstone is upper Turonian

Flores et al 1991: Gallup Sandstone (regressive) is lower delta-front, barrier, and tidal; middle coal-bearing delta-plain; upper progradational fluvial

Lawton 2004: positioned northeast of Bisbee rift shoulder (active during Morrison with feed into roundish basin, relict during Cretaceous with longitudinal feed along axis of foredeep and farther east)

Nummedal 2004: positioned northeast of Bisbee rift shoulder



after Molenaar (1983), Tschudy et al. (1984), Eaton and Nations (1991), Elder and Kirkland (1994), Nummedal (2004), Gradstein et al. (2004)

W.R. Dickinson unpublished notes on Laramide of the Colorado Plateau
Compiled by Jon Spencer, 2018

Figure N1 shows the main Laramide structures interior to the Colorado Plateau. Comparison with Figure B2 indicates that exposures of pre-Mesozoic strata outside the deeply incised Grand Canyon are confined to the cores of major uplifts (Circle Cliffs, Defiance, Kaibab, Monument, Nacimiento, Needles, San Rafael, Zuni). The monoclines with the greatest structural relief (East Defiance, East Kaibab, Hogback, San Rafael Reef, Waterpocket Fold, White River) form the flanks of major adjacent uplifts. The thickest successions of Tertiary strata were deposited within the depocenters of major Laramide basins (San Juan, Uinta), and the most extensive exposures of Cretaceous strata within the interior of the Colorado Plateau are preserved in downwarped keels of Laramide structural basins (Black Mesa, Henry). The net crustal shortening produced by the Laramide structures is estimated to be <5% and no more than 1% over large areas (Davis and Bump, 2009).

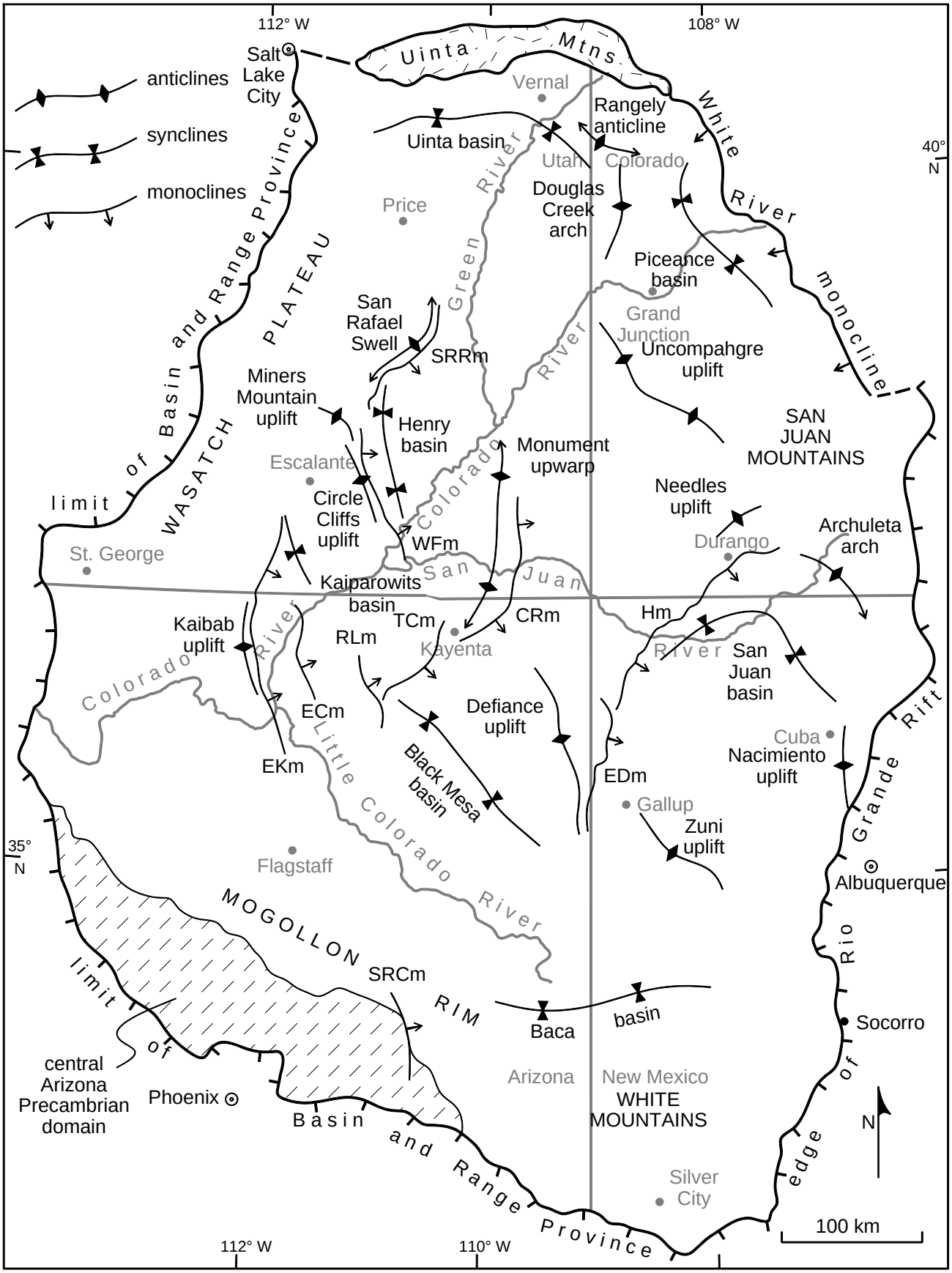
note: Figure B2 is figure 2 in Dickinson, 2018, GSA Special Paper 533

W.R. Dickinson unpublished notes, Laramide of the Colorado Plateau

Figure N1. Principal Laramide structural features of the Colorado Plateau adapted after Kelley (1955), Krantz (1989), Cather (2004), and Davis and Bump (2009). Monoclines: CRm–Comb Ridge, ECm–Echo Cliffs. EDm–East Defiance, EKm–East Kaibab, Hm–Hogback, RLm–Red Lake, SRCm–Salt River Canyon, SRRm–San Rafael Reef; TCm–Tsegi Canyon, WFm–Waterpocket Fold.

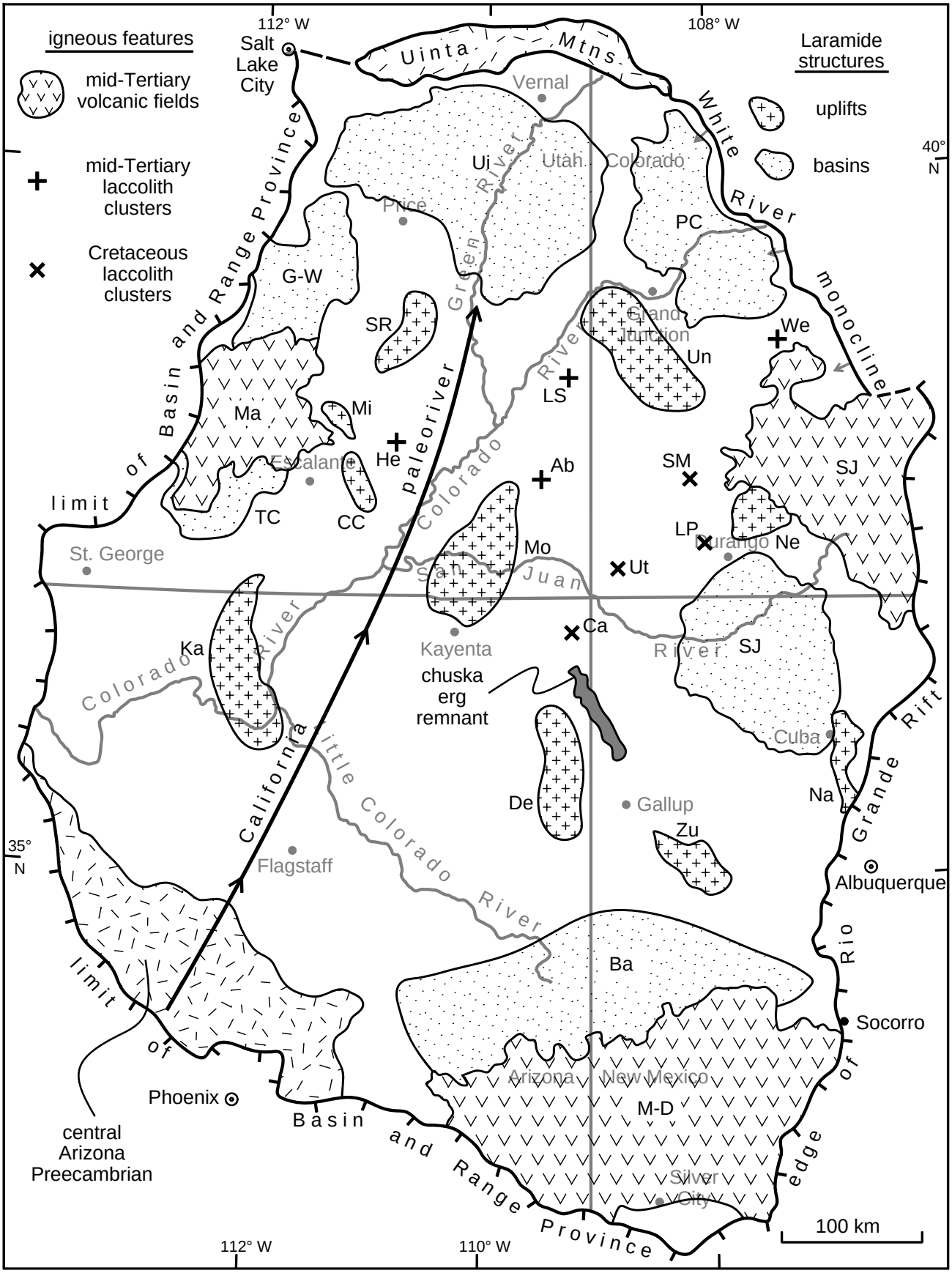
Figure N2. Laramide (Maastrichtian–Paleocene–Eocene) and mid-Tertiary (Oligocene–Early Miocene) uplifts, basins, and igneous centers of the Colorado Plateau: (a) Laramide uplifts (CC–Circle Cliffs, De–Defiance, Ka–Kaibab, Mi–Miners, Mo–Monument, Na–Nacimiento, Ne–Needles, SR–San Rafael, Un–Uncompahgre, Zu–Zuni); (b) Laramide basins (Ba–Baca, G-W–Gunnison-Wasatch Plateaus, PC–Piceance Creek, SJ–San Juan, TC–Table Cliff, Ui–Uinta); (c) mid-Tertiary volcanic fields (Ma– Marysvale, 31-24 Ma; M-D–Mogollon-Datil, 39-24 Ma; SJ–San Juan, 35-23 Ma); (d) Laramide (X) and mid-Tertiary (+) laccolith clusters(Ab–Abajo, 29-23 Ma; Ca–Carrizo, 74-70 Ma; He–Henry, 31-23 Ma; LP–La Plata, 68 Ma; LS–La Sal, 29-26 Ma; SM–San Miguel, 65-60 Ma; Ut, Ute, 72 Ma; WE, West Elk, 35-30 Ma). Laccolith ages from Cunningham et al. (1994), Garcia et al. (2010), Murphy et al. (2000), Nelson (1998), Nelson et al. (1992a, 1992b), Semken and McIntosh (1997), and Sullivan (1998). Chuska erg remnant after Dickinson et al. (2010b).

Figure N3. Regional setting of the Colorado Plateau (shaded) in relation to key Laramide (latest Cretaceous and Paleocene–Eocene) and mid-Tertiary (Oligocene and earliest Miocene) geotectonic features. Locations of Laramide uplifts and basins adapted after Dickinson et al. (1988) and Lawton (2008). Successive reconstructed positions of migratory post-Laramide volcanic fronts in the Basin and Range Province after Dickinson (2002, 2010, 2013b). The forearc basin trend includes the Great Valley–Transverse Ranges–Continental Borderland–Vizcaino Peninsula Cretaceous–Paleogene sedimentary accumulations as restored prior to Neogene offsets within the San Andreas transform system. See Figure N2 for the designation of Laramide uplifts and basins within the Colorado Plateau.



112° W
108° W
Salt Lake City
Uinta Mtns
anticlines
synclines
monoclines
Vernal
Rangely anticline
White River monocline
Uinta basin
Utah
Colorado
40° N
Douglas Creek arch
Price
Green River
Piceance basin
Grand Junction
San Rafael Swell
SRRm
Uncompahgre uplift
limit of Basin and Range Province
WASATCH PLATEAU
Miners Mountain uplift
Henry basin
Monument upwarp
SAN JUAN MOUNTAINS
Escalante
Colorado River
Circle Cliffs uplift
Needles uplift
Archuleta arch
Durango
WFm
St. George
San Juan
Kaiparowits basin
Hm
Kaibab uplift
TCm
CRm
RLm
Kayenta
San Juan basin
ECm
Defiance uplift
Cuba
Nacimiento uplift
EKm
Little Colorado River
Black Mesa basin
EDm
Gallup
Zuni uplift
Rio Grande Rift
35° N
Flagstaff
Albuquerque
MOGOLLON RIM
SRCm
Baca basin
Socorro
central Arizona Precambrian domain
Phoenix
Arizona
New Mexico
WHITE MOUNTAINS
Basin and Range Province
edge of
N
Silver City
100 km
112° W
110° W

Fig. N1



igneous features
mid-Tertiary volcanic fields
mid-Tertiary laccolith clusters
Cretaceous laccolith clusters
Laramide structures
uplifts
basins
112° W
108° W
110° W
40° N
35° N
Salt Lake City
Uinta Mtns
Vernal
Utah
Colorado
White River monocline
Ui
Price
PC
G-W
SR
Green River
Grand Junction
Un
We
LS
Ma
Mi
He
Escalante
TC
CC
paleoriver
Colorado River
Ab
SM
SJ
LP
Durango
Ne
Mo
Ut
St. George
San Juan River
Ca
Kayenta
Ka
Colorado River
chuska erg remnant
SJ
Cuba
Na
De
Gallup
Zu
Flagstaff
California
Little Colorado River
Albuquerque
Rio Grande Rift
Ba
Socorro
Arizona
New Mexico
M-D
Phoenix
central Arizona Preecambrian
Silver City
limit of Basin and Range Province
edge of Rio Grande Rift
100 km

Fig. N2

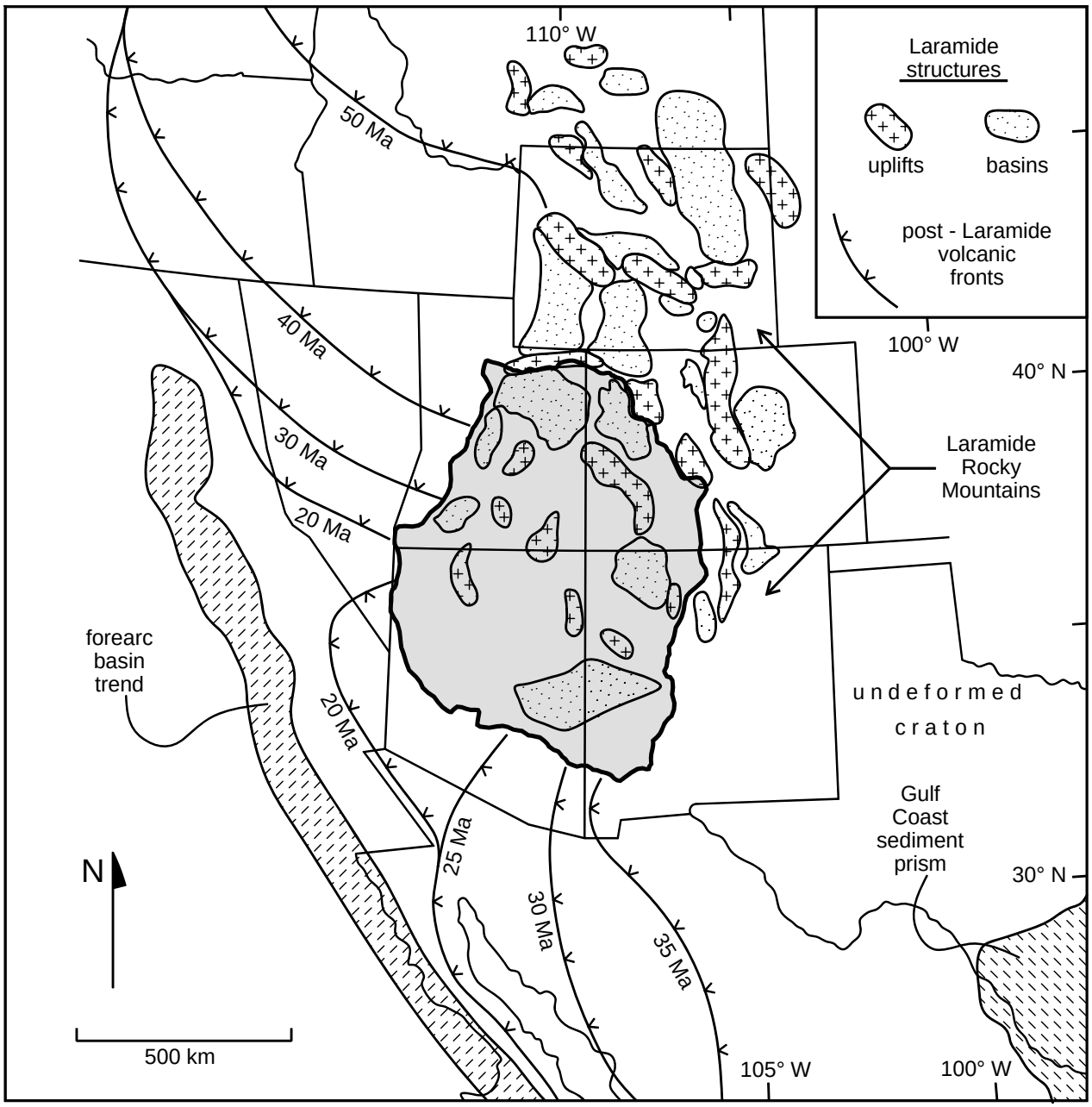

110° W
Laramide structures
uplifts
basins
post - Laramide volcanic fronts
50 Ma
40 Ma
30 Ma
20 Ma
100° W
40° N
Laramide Rocky Mountains
forearc basin trend
20 Ma
undeformed craton
Gulf Coast sediment prism
25 Ma
30 Ma
35 Ma
30° N
N
500 km
105° W
100° W

Fig. N3