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A flexural model for the Paradox Basin: implications for the tectonics of the Ancestral Rocky Mountains

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ABSTRACT

The Paradox Basin is a large (190 km × 265 km) asymmetric basin that developed along the southwestern flank of the basement-involved Uncompahgre uplift in Utah and Colorado, USA during the Pennsylvanian–Permian Ancestral Rocky Mountain (ARM) orogenic event. Previously interpreted as a pull-apart basin, the Paradox Basin more closely resembles intraforeland flexural basins such as those that developed between the basement-cored uplifts of the Late Cretaceous–Eocene Laramide orogeny in the western interior USA. The shape, subsidence history, facies architecture, and structural relationships of the Uncompahgre–Paradox system are exemplary of typical 'immobile' foreland basin systems.

Along the southwest-vergent Uncompahgre thrust, ~5 km of coarse-grained syntectonic Desmoinesian–Wolfcampian (mid-Pennsylvanian to early Permian; ~310–260 Ma) sediments were shed from the Uncompahgre uplift by alluvial fans and reworked by aeolian-modified fluvial megafan deposystems in the proximal Paradox Basin. The coeval rise of an uplift-parallel barrier ~200 km southwest of the Uncompahgre front restricted reflux from the open ocean south and west of the basin, and promoted deposition of thick evaporite-shale and biohermal carbonate facies in the medial and distal submarine parts of the basin, respectively. Nearshore carbonate shoal and terrestrial siliciclastic deposystems overtopped the basin during the late stages of subsidence during the Missourian through Wolfcampian (~300–260 Ma) as sediment flux outpaced the rate of generation of accommodation space. Reconstruction of an end-Permian two-dimensional basin profile from seismic, borehole, and outcrop data depicts the relationship of these deposystems to the differential accommodation space generated by Pennsylvanian–Permian subsidence, highlighting the similarities between the Paradox basin-fill and that of other ancient and modern foreland basins. Flexural modeling of the restored basin profile indicates that the Paradox Basin can be described by flexural loading of a fully broken continental crust by a model Uncompahgre uplift and accompanying synorogenic sediments. Other thrust-bounded basins of the ARM have similar basin profiles and facies architectures to those of the Paradox Basin, suggesting that many ARM basins may share a flexural geodynamic mechanism. Therefore, plate tectonic models that attempt to explain the development of ARM uplifts need to incorporate a mechanism for the widespread generation of flexural basins.

INTRODUCTION

The Ancestral Rocky Mountains (ARM) are a mosaic of approximately 20 basement-involved arches and thrust-bounded structural highs that extend from southern Idaho to central Texas, in the western interior USA (Fig. 1). Between these uplifts are locally thick successions of coarse-grained syntectonic sediments, the ages of which have been used to date the ARM orogenic event as Pennsylvanian–Permian (Late Carboniferous) (Mallory, 1958). The ARM uplifts have up to 5 km of structural relief. Despite their structural prominence, the tectonic development of the ARM uplifts remains poorly understood, partly due to the protracted history of tectonism that has affected the U.S. Cordillera since the Middle Paleozoic.

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Kluth & Coney (1981) and Kluth (1986) suggested that the ARM developed within an escape tectonic regime in the foreland of the northwest-vergent Ouachita–Marathon thrust system. In contrast, Ye *et al.* (1996) suggested that the northwest-striking elements of the ARM are better explained by northeast-directed shallow-angle subduction that may have occurred along the southwestern margin of

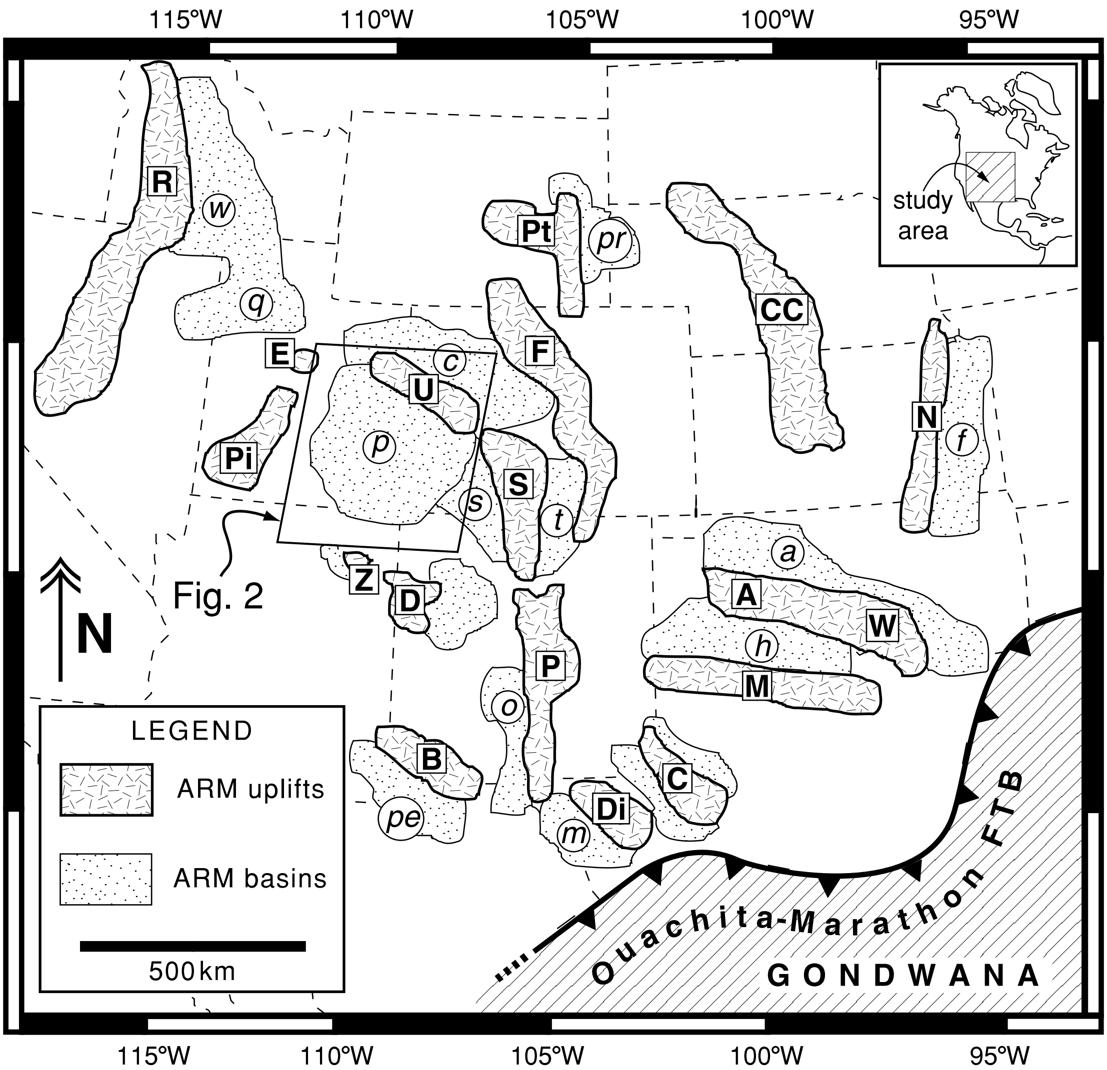

Fig. 1. Location of major Late Paleozoic tectonic elements, southern and western United States. Ancestral Rocky Mountain (ARM) uplifts indicated by hashured pattern and labeled with capital letters in boxes: U: Uncompahgre uplift, R: Roberts Mountain Allochthon, E: Emery uplift, Pi: Piute uplift, Z: Zuni uplift, D: Defiance uplift, B: Burro uplift, P: Pedernal uplift, S: San Luis uplift; F: Frontrange uplift, Pt: Pathfinder uplift, CC: Cincinati Arch/Central Kansas uplift, A/W: Amarillo–Wichita uplifts, M: Matador/Red River uplifts, C: Central Basin Platform, Di: Diablo uplift, N: Nemeha arch. Ancestral Rocky Mountain intraforeland Basins indicated by dotted pattern and labeled with lowercase italicized letters in circles: *p*: Paradox Basin, *w*/*q*: Wood River–Oquirrh Basins, *c:* Central Colorado Trough, S: San Juan Trough, *pe*: Pedregosa Basin, *O*: Orogrande Basin, *t*: Taos Trough, *pr*: Powder River Trough, *m*: Marfa Basin, *h*: Hardeman/Palo Duro Basins, *a*: Anadarko Basin, *f*: Forest City Basin. Location of Fig. 2 shown in box.

North America. Whereas geological evidence for an active Pennsylvanian–Permian southwestern margin is meager and debated (Kluth, 1998), the work of Ye *et al.* (1996) has emphasized the poorly understood nature of the ARM tectonic system.

Existing tectonic models have not taken full advantage of the geodynamics of intermontane ARM basins, which should be sensitive indicators of the regional tectonic setting. In this paper, I focus on one of the largest and best exposed of the ARM basins, the Paradox Basin of eastern Utah and western Colorado (Figs 1 and 2). The Paradox Basin is best explained as a localized flexural basin, similar to many intraforeland flexural basins that developed during the Late Cretaceous to Eocene Laramide orogeny in the North American Cordillera (Hagen *et al.*, 1985; Hall & Chase, 1989). Although other ARM basins have not been analyzed by flexural modeling, the contractional deformational styles of their associated uplifts (Brewer *et al.*, 1983; Lindsey *et al.*, 1986; Yang & Dorobek, 1995; Hoy & Ridgway, 2002) and the similarities between the ARM and Laramide-style intraforeland flexural basins have led to interpretations of widespread ARM flexural subsidence (Armin, 1987; Soegaard, 1990; Yang & Dorobek, 1995; Geslin, 1998; Hoy & Ridgway, 2002). The recognition of flexural subsidence in the Paradox and other ARM basins requires that any tectonic model for the ARM orogenic event must account for widespread and far-field shortening.

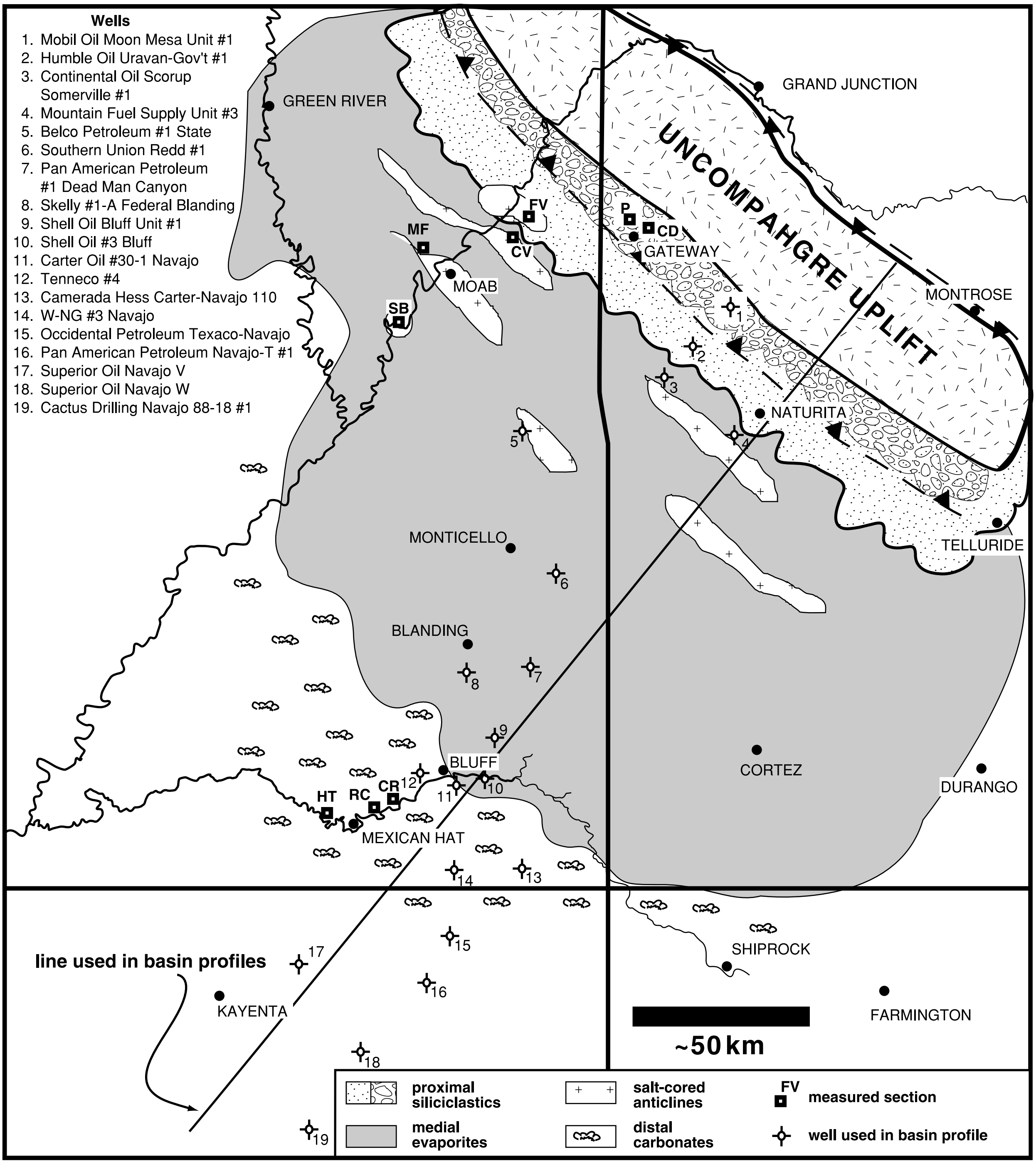

Fig. 2. Location map of Uncompahgre-Paradox system. Sites of measured sections and observation localities indicated by boxes. CD: Casto Draw, P: Palisades, FV: Fisher Towers and Fisher Valley, CV: Castle Valley, MF: Moab Fault along Highway 191, SB: Shafer and Lockhart basins, CR: Comb Ridge reach of San Juan River, RC: Raplee Canyon reach of San Juan River, HT: Honaker Trail and Goosenecks. Well symbols depict wells used in basin profile reconstruction.

REGIONAL SETTING AND PREVIOUS MODELS

The Paradox Basin is a ~5×10^4 km^2 asymmetric basin that developed along the southwestern flank of the Uncompahgre uplift (Figs 1 and 2) during mid-Pennsylvanian through early Permian time (Wengerd, 1962; Lemke, 1985; Stevenson & Baars, 1986). The Uncompahgre uplift (Fig. 2) is a 50-km wide NW–SE-trending basement-involved arch, bounded on the southwest and northeast by 200–300 km long fault zones that are largely buried by synorogenic and subsequent deposits. The southwestern uplift-bounding fault is the moderately NE-dipping Uncompahgre fault, which displays top-to-the-southwest relative displacement and ~10 km of NE–SW shortening in the form of a crystalline basement overhang in the most proximal Paradox Basin (Frahme & Vaughn, 1983; White & Jacobson, 1983). The northeastern uplift-bounding fault is subvertical near the surface, shows top-to-the-northeast relative displacement (Waechter & Johnson, 1986), and probably branches from the Uncompahgre fault in the subsurface.

Development of all of the ARM uplifts and their associated basins (Fig. 1) was coeval with northeast-to-southwest zippering of the suture between northern Gondwana and southern North America along the Appalachian–Ouachita–Marathon fold-thrust belt (Graham *et al.*, 1975; Ross, 1979; Kluth, 1986). Many ARM uplifts and basins were reactivated and/or overprinted by deformation of a similar style during the Late Cretaceous–Eocene Laramide orogeny; in this paper, I will deal strictly with the Pennsylvanian–Permian phase of deformation and deposition.

Stevenson & Baars (1986) proposed that the Paradox Basin, one of the ARM's largest, developed by pull-apart tectonism in the distal foreland of the Ouachita–Marathon belt, thus supporting the escape tectonic model of Kluth & Coney (1981). In the Stevenson & Baars model, subsidence is attributed to strike-slip offset along a releasing bend located on the southwestern margin of the Uncompahgre uplift. The kinematics, geometry and subsidence history of the Paradox Basin, however, are not easily interpreted using the pull-apart model.

The Paradox Basin is both larger and wider than well-documented modern and ancient pull-apart basins. Aydin & Nur (1982) compiled pull-apart basin plan-view geometries and found that such basins range in width from 0.01 to 80 km and have an aspect ratio of ~3 : 1, independent of scale. Updated pull-apart and foreland basin geometric data are compiled in Table 1 and are consistent with Aydin and Nur's findings. These data suggest that isolated flexural basins are considerably wider than pull-apart basins and have a more equidimensional aspect ratio (~1.75). With a width of 180–200 km and an aspect ratio of ~1.4, the Paradox Basin is more similar to isolated flexural basins than typical pull-apart basins (Fig. 3).

If indeed the Paradox were a pull-apart basin, its large width would require a dominant component of thermotectonic (as opposed to strictly mechanical) subsidence (McKenzie, 1978; Pitman & Andrews, 1985), which would be accompanied with extension-related magmatism. One of the problems that have complicated our understanding of the ARM is its distinct lack of magmatism, which limits the application of both shallow-angle subduction regional tectonic models (i.e. the Ye *et al.* model) and models that ascribe basin subsidence to thermal relaxation. Moreover, Lemke (1985) conducted a quantitative subsidence analysis of six stratigraphic sections from widely spaced parts of the Paradox Basin that further argues against large-scale pull-apart tectonism. Whereas Lemke confirmed that the subsidence rate recorded by strata of the Paradox Basin's distal margin is compatible with thermotectonic subsidence, the subsidence rates recorded by the stratal architecture of the proximal (Uncompahgre-bounding) parts of the basin are too rapid to be explained by thermal relaxation. This led Lemke to suggest that the differential subsidence in the Paradox Basin might be better explained by flexure of the lithosphere by supracrustal loading from the Uncompahgre uplift.

Although a pull-apart origin for the Paradox Basin seems unlikely, it is difficult to disqualify the possibility of some component of strike-slip displacement along the Uncompahgre fault. Nonetheless, geometric evidence suggests that deformation in the proximal Paradox Basin was dominantly of a contractional, dip-slip sense. Robust piercing points that might record the magnitude and sense of Late Paleozoic slip along the Uncompahgre fault are not visible in the local surface geology, although provenance data from proximal Paradox Basin deposits (Mack & Rasmussen, 1984) suggest that the amount of strike-slip offset is minimal. The modern topography of the crystalline Precambrian hangingwall of the Uncompahgre fault near Gateway, Colorado (Fig. 2) reveals only local exposures of a distinctive Precambrian quartz monzonite porphyry within the dominantly granitic and schistose core of the Uncompahgre uplift. Mack & Rasmussen (1984) documented spherical boulders of this monzonite porphyry throughout a vertical stratigraphic section of the proximal basin, directly down-dip from its source. Similarly, on the northeastern side of the Uncompahgre uplift along the margins of the Central Colorado Trough and Eagle Basin, Lindsey *et al.* (1986) reported negligible lateral offset between Pennsylvanian–Permian sediments with distinctive pink quartz monzonite porphyry clasts in the proximal basin and their locally exposed source to the southwest across the basin-bounding fault within the Precambrian basement of the Uncompahgre uplift.

Additionally, borehole and two-dimensional seismic data from the southwestern Uncompahgre structural front have revealed the presence of a moderately NE-dipping thrust fault that has ~10 km of southwestward heave, placing Precambrian crystalline basement over the most proximal basin-fill (Frahme & Vaughn, 1983; White & Jacobson, 1983). With the aid of high-resolution three-dimensional seismic volumes and robust well control, many ARM features in the subsurface of the southern mid-continent that were formerly recognized as transpressional 'flower-structures' have been recently reinterpreted as contractional structures with little to no strike-slip offset (B. Sralla, C. Saxon, S. Decker, pers. comm.). These structures bear a striking resemblance to the basin-bounding thrust structures of the classic ARM (e.g. Uncompahgre, Ancestral Frontrange, etc.), which reside 1000–1500 km along-strike to the northwest.

FACIES ARCHITECTURE OF THE PARADOX BASIN

The structure, stratigraphy and paleontology of the Paradox Basin have been documented by Kelley (1955), Wengerd & Matheny (1958), Hite (1960), Wengerd (1962), Pray & Wray (1963), Elias (1963), Peterson &

Table 1. Length, width and aspect ratio data for various pull-apart and isolated foreland basins.

Basin type	Basin	Length (km)	Width (km)	Aspect ratio	Reference
Pull-apart basins	Amora, Dead Sea	55	18	3.06	Manspeizer (1985)
	Ancenis, France	40	10	4.00	Diot & Blaise (1978)
	Aragonese, Gulf of Elat	40	9	4.44	Ben-Avraham *et al.* (1979)
	Bowser, Canadian Cordillera	470	120	3.92	Eisbacher (1985)
	Brawley, San Andreas Fault (SAF)	10	7	1.43	Johnson & Hadley (1976)
	Central, Spitzbergen	160	50	3.20	Steel *et al.* (1985)
	Cholame Valley, SAF	17	3	5.67	Brown (1970)
	Elat, Gulf of Elat	45	10	4.50	Ben-Avraham *et al.* (1979)
	Erzincan, N. Anatolian Fault (NAF)	40	12	3.33	Ketin (1969)
	Glynnwe Lake, New Zealand	1.8	0.5	3.60	Freund (1971)
	Hemet, SAF	22	5	4.40	Sharp (1975)
	Hornelen, Norway	65	18	3.61	Nilsen & McLaughlin (1985)
	Hula, Dead Sea	20	7	2.86	Freund *et al.* (1968)
	Karkom, Israel	18	6	3.00	Bartov (1979)
	Koehn Lake, SAF	40	11	3.64	Aydin & Nur (1982)
	La Gonzales Venezuela	23	6.2	3.71	Schubert (1980)
	Lago de Izabal, Guatemala	80	30	2.67	Aydin & Nur (1982)
	Lake Valencia, Venezuela	30	11.5	2.61	Schubert & Laredo (1979)
	Little Sulphur Creek, SAF	12	2	6.00	Nilsen & McLaughlin (1985)
	Medway-Karaka, New Zealand	0.7	0.2	3.50	Freund (1971)
	Merida-Mucuchies, Venezuela	6.2	1.7	3.65	Schubert (1980)
	Mora, Spain	68	30	2.27	this paper
	Mortagne, France	47	19	2.54	Guineberteau *et al.* (1987)
	Motagua, Guatemala	50	20	2.50	Schwartz *et al.* (1979)
	Niksar, NAF	25	10	2.50	Aydin & Nur (1982)
	Nonacho, Canada	180	40	4.50	Aspler & Donaldson (1985)
	Ridge, SAF	35	10	3.50	Nilsen & McLaughlin (1985)
	San Nicholas, offshore SAF	68	30	2.27	Christie-Blick & Biddle (1985)
	Sedom, Dead Sea	70	30	2.33	Manspeizer (1985)
	Soria, Spain	70	50	1.40	Guiraud & Seguret (1985)
	Susheri, NAF	23	6	3.83	Ketin (1969)
	Vienna, Central Europe	160	30	5.33	Royden (1985)
	Pull-apart averages	78	24	3.43	
Isolated foreland basins	Paradox, Four Corners, USA	265	190	1.39	this paper
	Sevier, Idaho and Nevada	1350	1040	1.30	Sloss (1988)
	Sevier, Utah and Idaho	780	390	2.00	Sloss (1988)
	Sevier, Idaho	520	390	1.33	Sloss (1988)
	Black Warrior, Applachian-Ouachita	230	160	1.44	Sloss (1988)
	Anadarko, Wichita-Amariilos	390	182	2.14	Thomas (1988)
	Fort Worth, Marathons	208	182	1.14	King & Edmonston (1972)
	Val Verde, Marathons	480	225	2.13	Sloss (1988)
	Antler, Idaho and Nevada	598	364	1.64	King & Edmonston (1972)
	Powder River, Wyoming	300	200	1.50	Sloss (1988)
	Bighom, Wyoming	210	140	1.50	King & Edmonston (1972)
	Denver, Colorado	460	280	1.64	King & Edmonston (1972)
	Uinta, Utah	180	150	1.20	Baars (1988)
	Appalachian, Virginia and Pennsylvania	936	468	2.00	Sloss (1988)
	Ouachita, Arkansas and Oklahoma	450	180	2.50	Sloss (1988)
	Arkoma, Arkansas and Oklahoma	360	150	2.40	King (1975)
	Indus, India and Pakistan	1050	550	1.91	DeCelles *et al.* (1998)
	Ganges, India and Nepal	700	300	2.33	DeCelles *et al.* (1998)
	Denver, Colorado	180	115	1.57	Dickinson *et al.* (1988)
	Crazy Mts, Montana	95	55	1.73	Dickinson *et al.* (1988)
	Bull Mtn, Montana	65	35	1.86	Dickinson *et al.* (1988)
	Green River, Wyoming	200	110	1.82	Dickinson *et al.* (1988)
	Foreland basin averages	464	270	1.75	

Hite (1969), and Condon (1997), among others. Three conformable lithostratigraphic units compose the basin-fill (Fig. 4): the carbonate and evaporite facies of the Paradox Formation; the mixed siliciclastic and carbonate Honaker Trail Formation; and the siliciclastic Cutler Group (the undivided Cutler Formation in the proximal basin). The lower portion of the proximal Cutler combines with the evaporite and carbonate facies of the Paradox Formation to create a tripartite Desmoinesian (~310–305 Ma) system, during the deposition of which the majority of basin subsidence and sediment accumulation occurred. Lithofacies and measured stratigraphic sections (Figs 5 and 6) of these and overlying facies associations from nine localities across the basin (Fig. 2) combine with the existing literature to provide the following chronostratigraphic interpretation of facies architecture. Table 2 outlines the typical lithofacies of the basin-fill and the variations of these lithofacies across the basin.

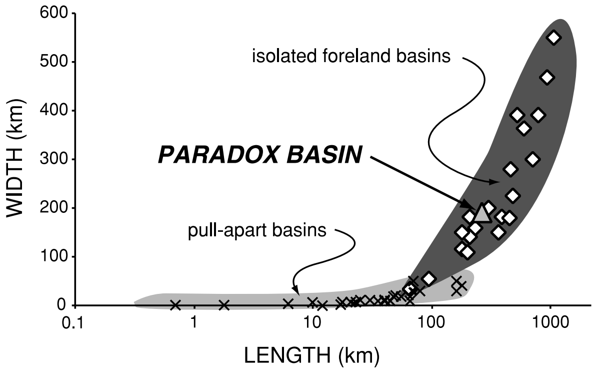

Fig. 3. Plot of the length and width dimensions of various modern and ancient isolated flexural and pull-apart basins. The average aspect ratio of pull-apart basins plotted here is 3.61. The average for isolated flexural basins is 1.75. The Paradox Basin (gray triangle) plots well within the flexural basin field. Data and references for this plot are included in Table 1.

Tripartite Desmoinesian basin-fill

Proximal Cutler Formation

Proximal to the structural front of the Uncompahgre uplift, the Cutler Formation is composed of a thick (up to ~5 km) succession of boulder to pebble, arkosic conglomerate and subordinate trough cross stratified, very coarse-grained sandstone (Fig. 5). This coarse facies

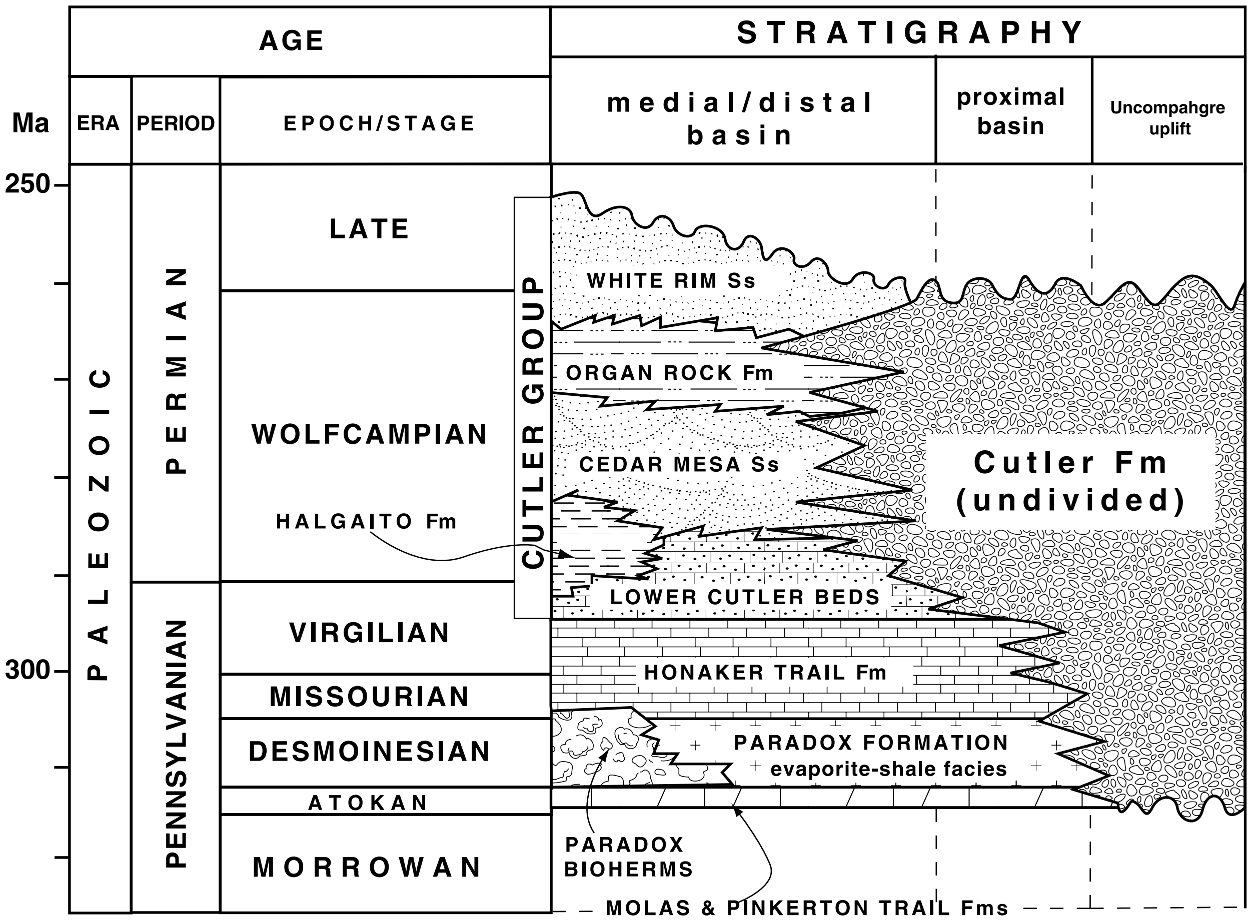

Fig. 4. Stratigraphic column of basin-fill units in the Paradox Basin. Compiled from Wengerd & Matheny (1958), Welsh (1958), Pray & Wray (1963), Elias (1963), Peterson & Hite (1969) and Condon (1997).

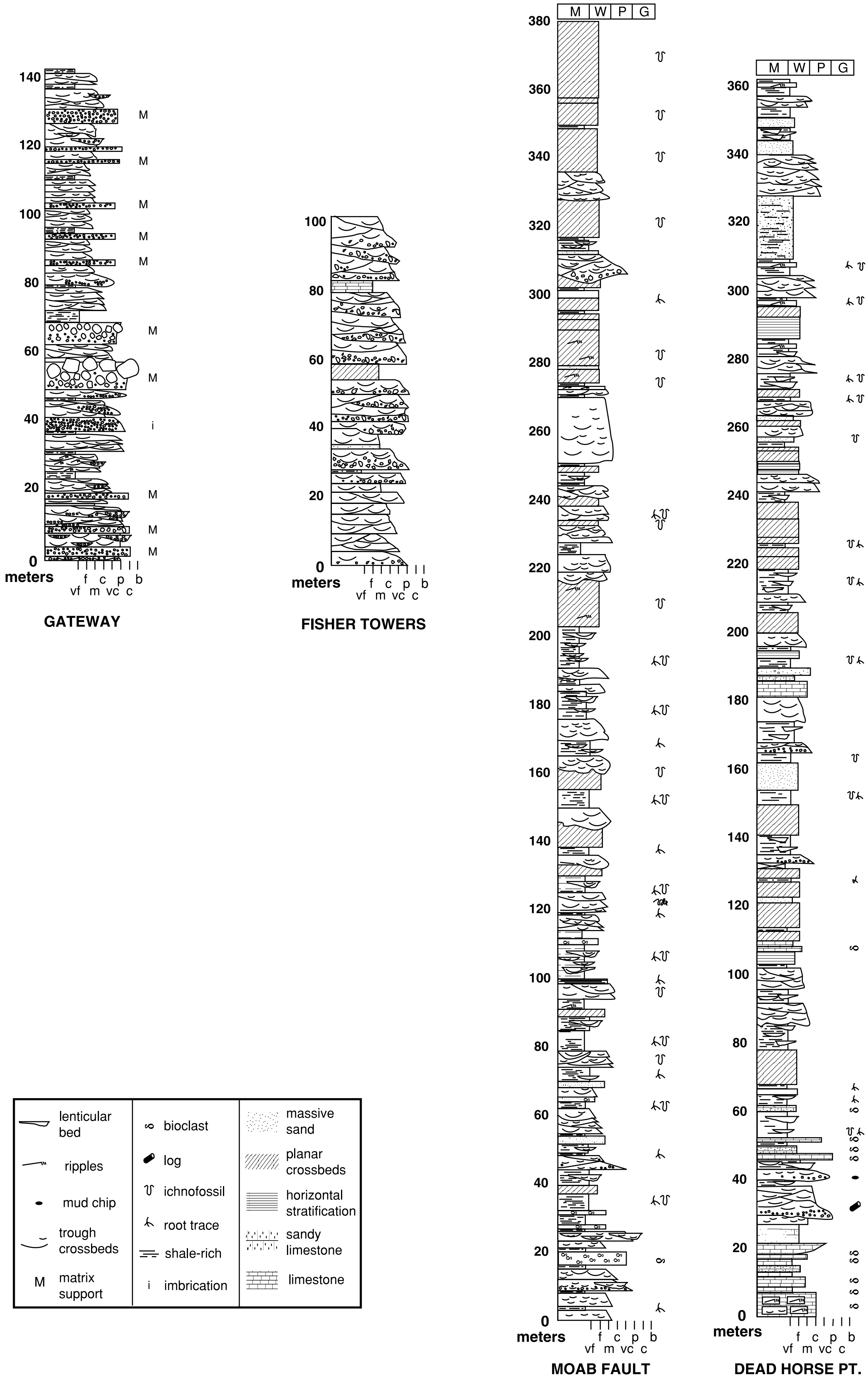

Fig. 5. Representative (partial) measured sections of proximal Cutler Formation at Gateway (Palisades), Fisher Towers, Moab Fault and Dead Horse Point (Shafer Basin) localities.

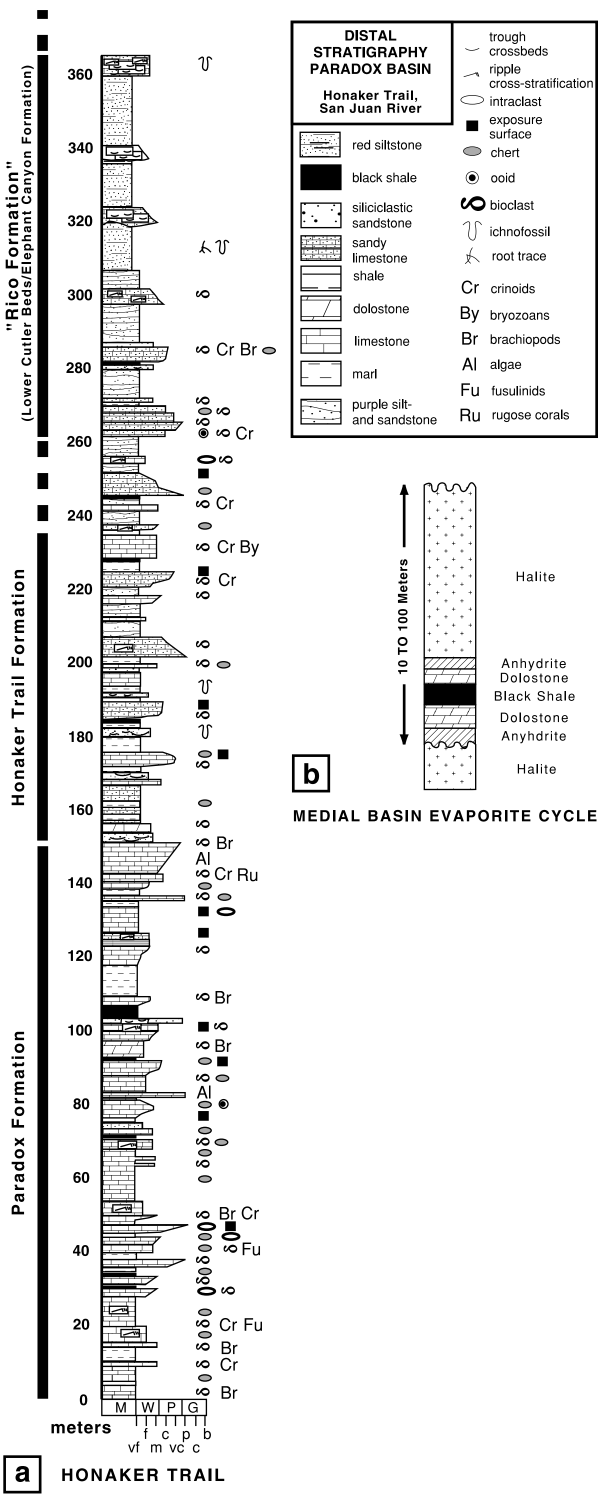

Fig. 6. (a) Representative measured sections of distal Paradox, Honaker Trail and 'Rico' Formations (Lower Cutler Beds) from Honaker Trail locality. (b) Typical evaporite cyclothem of Paradox Formation in subsurface of medial basin. Modified from Peterson & Hite (1969).

thins and fines gradually towards the southwest away from the structural front of the Uncompahgre uplift. The lower parts of the Cutler Formation interfinger with the evaporite facies of the Desmoinesian Paradox Formation (~310–305 Ma), and its upper part grades laterally into the Missourian–Virgilian (~305–295 Ma) Honaker Trail Formation and Virgilian– Wolfcampian (~295–260 Ma) Cutler Group of the medial and distal basin. The proximal Cutler Formation is usually mapped as part of the undivided Permian Cutler Formation, owing to its red color and lateral association with the Cutler Group (Condon, 1997). However, well-log correlation of marker shale units (Peterson & Hite, 1969; White & Jacobson, 1983) and lateral intertonguing relationships with documented Middle to Upper Pennsylvanian units (Elston *et al.*, 1962; Franczyk *et al.*, 1995) suggest that deposition of this proximal unit was also synchronous with deposition of the Desmoinesian Paradox Formation and the Desmoinesian to Virgilian Honaker Trail Formation (Fig. 4).

Mack & Rasmussen (1984) interpreted the proximal Cutler Formation near Gateway as parts of a 'dry' alluvial fan composed of sediment shed from the Uncompahgre uplift in a southwestward direction. In the larger Gateway section, the relative abundance of gravelly sandstone facies and clast-supported, cross-stratified, and imbricated cobble conglomerates and the paucity of matrix-supported debris flow deposits suggest that outside localized fanhead trenches the Gateway fan was dominated by traction flow processes. The prevalence of trough cross-stratified, clast-supported conglomerate and very coarse sandstone in an 80-km wide southeast-trending swath just down-dip from the southwestern margin of Uncompahgre uplift (Wengerd, 1962; Campbell, 1980; White & Jacobson, 1983; Condon, 1997) suggests that the proximal Cutler Formation was deposited by a system of coalesced stream-dominated alluvial fans and fluvial megafans that reworked boulder and cobble gravels shed from the crystalline basement of the Uncompahgre uplift. The protracted (~30 Myr) deposition of this coarse, thick unit alongside the Uncompahgre uplift recorded the complete contractional development of the basement-involved structure.

Paradox Formation

Evaporite-shale and biohermal carbonate facies of the medial and distal basin, respectively, combine with the coarse arkosic proximal facies described above to define the tripartite Desmoinesian system that recorded the most active phase of subsidence and contractional tectonism in the Paradox Basin. In the medial basin, the Paradox Formation is a thick (up to ~3 km) megasequence of 29 shale-dolomite-evaporite cyclothems (Peterson & Hite, 1969). Although rarely exposed in outcrop, these cycles (Fig. 6b) are identifiable in well logs from boreholes drilled across the basin (Fig. 2).

Bounded by disconformities, these glacio-eustatically driven cycles (Dickinson *et al.*, 1994; Goldhammer *et al.*, 1994) were interpreted by Hite (1960, 1970) and Peterson & Hite (1969) as subaqueous restricted-marine deposits. Differential loading by prograding fans (Ge *et al.*, 1997) of the proximal basin instigated halokinetic rise of the

Table 2. Lithofacies and deposystems of the Pennsylvanian–Permian Paradox Basin.

UNIT	AGE	LOCATION (refer to Fig. 2)	LITHOFACIES	DEPOSYSTEM INTERPRETATION	FORELAND BASIN INTERPREATION	REFERENCES
Proximal Cutler Fm	Desmoinesian–Wolfcampian	Gateway, CO: Casto Draw	– gray, thick, massive, matrix-supported, very poorly sorted, boulder to pebble conglomerate – subordinate cross-stratified, lenticular, coarse sandstone	alluvial fan fanhead trench	synsubsidence proximal foredeep	Mack & Rasmussen (1984); Shultz (1984)
Proximal Cutler Fm	Desmoinesian–Wolfcampian	Gateway, CO: Palisades	– moderately sorted, gray to red, clast-supported, arkosic cobble conglomerate – broadly lenticular beds of well-sorted, thickly bedded, coarse sandstone – subordinate matrix-supported poorly sorted conglomerate	stream-dominated alluvial fan/ fluvial megafan	synsubsidence proximal foredeep	Mack & Rasmussen (1984); Shultz (1984)
Proximal Cutler Fm	Desmoinesian–Wolfcampian	Fisher and Castle Valleys	– red-brown, well-sorted, coarse sandstone with subordinate imbricated pebble to cobble conglomerate	proximal fluvial megafan	synsubsidence medial foredeep	Campbell (1980); White & Jacobson (1983); Condon (1997)
Paradox Fm evaporites	Desmoinesian	subsurface	– shale-dolomite-evaporite cyclothems	restricted to open marine pelagic	synsubsidence medial foredeep	Peterson & Hite (1969); Hite (1970); Dickinson *et al.* (1994); Goldhammer *et al.* (1994)
Paradox Fm carbonates	Desmoinesian	Honaker Trail, Raplee Canyon, Comb Ridge	– laminated sapropelic marls and carbonate mudstones – phylloid algal, foraminiferal, oolitic, chert-rich wackestones, packstones and grainstones – lenticular-bedded calcite-cemented quartzose sandstones – cross-stratified, oxidized and/or brecciated calcarenites	biohermal & biostromal carbonates	synsubsidence distal foredeep/forebulge	Welsh (1958); Pray & Wray (1963); Peterson & Hite (1969); Peterson & Ohlen (1963)

Table 2. (*Contd.*)

UNIT	AGE	LOCATION (refer to Fig. 2)	LITHOFACIES	DEPOSYSTEM INTERPRETATION	FORELAND BASIN INTERPRETATION	REFERENCES
Honaker Trail Fm and 'Lower Cutler Beds'/ Rico Fm	Missourian–Virgilian	Honaker Trail, Raplee Canyon, Comb Ridge, Shafer Basin, Moab Fault	– grey bioclastic (crinoid, fusulinid, bryozoan, brachiopod) packstones – broadly lenticular coated-grainstones – broadly lenticular, cross-stratified calcarenites – red, green and purple siltone and sandstone – green marl and black, sapropelic, calcareous mudstones – red, gray, and white chert nodules	mixed siliciclastic and carbonate shoals and coastal plain	late synsubsidence medial to distal foredeep	wengerd & Matheny (1958); Baars (1961); Condon(1997); Tidwell (1988)
Medial Cutler Fm	Wolfcampian	Moab Fault, Shafer Basin, Deadhorse Pt	– massive, tabular, fine-grained, planar cross-stratified orange sandstones – coarse, well-sorted, lenticular beds of maroon sandstones and pebble conglomerates – brown siltstones	eolian, Playa, distal fluvial megafan	overfilled basin succession	Condon (1997)
Cutler Group	Wolfcampian–Late Permian	Honaker Trail, Raplee Canyon, Comb Ridge	– well-sorted siltstones and subordinate sandstones – massive, cross-stratified, fine-grained quartzose sandstones	terrestrial redbeds and eolianites	overfilled basin succession	Murphy (1987); Condon (1997)

Paradox Formation evaporites soon after their deposition, developing salt-cored anticlines and accompanying growth structures in the upper Paleozoic and lower Mesozoic section of the Moab, Utah area (Shoemaker *et al.*, 1958). In many parts of the medial basin, halokinesis has obscured the original depositional thickness of the evaporite facies, although autochthonous sections of ~2.2 km or more have been identified (Peterson & Hite, 1969).

Contemporaneous with evaporite deposition (Hite, 1970), a ~350-m thick succession of shelf carbonates and interbedded sapropelic shales developed on the distal southwestern basin margin (Fig. 6). Representative depositional cycles in the distal basin generally begin with interbedded, laminated, sapropelic marls and carbonate mudstones and wackestones that coarsen and thicken upward into massive, fossiliferous and chert-rich units that range from wackestone to grainstone in texture. These phylloid-algal (Elias, 1963; Pray & Wray, 1963), foraminiferal, oölitic (Peterson & Ohlen, 1963) and bioclastic units often have low-amplitude, long-wavelength biohermal forms and are frequently capped by cross-stratified, oxidized and/or brecciated beds. Locally, lenticular calcite-cemented quartzose sandstones are intercalated with these massive carbonate units (Fig. 6a).

Fusulinid and bryzoan faunas preserved throughout the distal carbonate facies ascribe a Desmoinesian (~310–305 Ma) age for the Paradox carbonates (Welsh, 1958). The contiguous sapropelic mudstones allow for correlations between distal carbonate and medial evaporite cyclothems (Peterson & Hite, 1969). These correlations, when coupled with the interbedding of coarse arkosic and evaporite units in the proximal-medial basin, suggest that the tripartite Desmoinesian system records the onset and maximum development of Paradox Basin subsidence. Variations in Desmoinesian interval thicknesses – from > 4 km in the proximal basin to ~350 m in the distal basin – support interpretations of long-wavelength differential subsidence during this time.

Honaker Trail Formation

Following deposition of the Paradox Formation, remaining accommodation space in the distal ~150 km of the basin was filled by the Missourian–Virgilian Honaker Trail Formation. Distinguished in outcrop from the distal carbonate facies of the Paradox Formation by its less massively bedded strata, higher siliciclastic content, and abundance of primary physical sedimentary structures (Fig. 6), the Honaker Trail Formation (Wengerd & Matheny, 1958) is a southwest tapering carbonate-dominated unit that covered the evaporite-shale and biohermal carbonate facies of the Desmoinesian system, thereby preserving the underlying depositional topography.

The Honaker Trail Formation is generally composed of successions of gray bioclastic packstones, coated grainstones and calcarenites interbedded with slope-forming successions of red, green and purple siltstone and sandstone with green marl and black, sapropelic, calcareous mudstones. Calcarenitic and coated grainstone beds often have broadly lenticular geometries and are abundantly cross-stratified. Massive carbonate packstones are locally rich in crinoid, brachiopod, fusulinid and bryozoan faunas, as well as red, gray, and white chert nodules. Boundstone textures are rare in comparison to the Paradox Formation. In the upper Honaker Trail Formation (i.e. the Rico Formation of Cross & Spencer, 1900; and/or the Elephant Canyon Formation of Baars, 1961; and/or the Lower Cutler beds of Loope *et al.*, 1990; Condon, 1997), typical carbonate units are increasingly intercalated with thick, lenticularly bedded, cross-stratified, quartzose and mottled red sandstones and siltstones.

The abundance of cross-stratified calcarenites, lenticular bedding geometries and disaggregated and coated bioclasts suggest that the Honaker Trail Formation was deposited by intertonguing carbonate shoals and coastal channels on a broad shelf offshore of the terrestrial fan systems that continued to dominate deposition in the proximal basin during Late Pennsylvanian time. The Honaker Trail Formation records the transition from a localized Middle–Late Pennsylvanian marine and restricted marine deposystem to the regionally expansive, terrestrial Permian system recorded by the overlying Cutler Group.

Cutler Group

Outside of the proximal-medial portion of the Paradox Basin where the undivided Cutler Formation occupies a ~5-km thick portion of the stratigraphic section, the Cutler Group is a ~530-m thick, complex mosaic of interfingering buff, orange, red, and maroon, arkosic and quartzose sandstones and siltstones of Permian age. Work by Condon (1997) summarizes the members and facies of these primarily fluvial and eolian strata.

The Wolfcampian Cutler Group of the medial and distal basin is significantly thinner than Desmoinesian–Wolfcampian rocks of the proximal Cutler Formation. Condon (1997) interpreted the resulting isopach pattern as an artifact of the structural damming of arkosic sediments by halokinetic deformation of the Paradox evaporites in the medial basin. It is likely that trapping of coarse material along the structural front of the Uncompahgre uplift by the rapid subsidence rates of the proximal foredeep also contributed to restricting the expansion of the Cutler Group until after the available accommodation space in the proximal basin was filled. Along with time-equivalent parts of the proximal Cutler Formation, the Cutler Group records the bypassing of the proximal basin by arkosic redbed sediments shed from the Uncompahgre uplift and deposited by an elaborate Wolfcampian fluvio-eolian depositional system. This basin-wide deposition was fuelled by untapped sediment supply coffers in the still-high Uncompahgre and precluded further intrabasinal carbonate sedimentation. Moreover, its conclusion marked the end of sediment accumulation related strictly to localized Pennsylvanian–Permian Paradox Basin subsidence.

THE PARADOX BASIN AS AN INTRAFORELAND FLEXURAL BASIN

A number of workers have suggested that flexure may have influenced the development of the Paradox Basin (Ohlen & McIntyre, 1965; Szabo & Wengerd, 1975; Lemke, 1985; Jackson *et al.*, 1998) as well as other ARM basins (Armin, 1987; Soreghan, 1994; Geslin, 1998; Gallardo & Blackwell, 1999; Hoy & Ridgway, 2002). However, the geometry and facies architecture of the Paradox Basin have not been thoroughly examined in the context of flexural response features and their accompanying depozones.

Foreland basins are elongate regions of potential sediment accumulation that form in response to geodynamic processes related to the development of a local orogenic belt (DeCelles & Giles, 1996). Commonly, crustal flexure is modeled as the response to the development of a topographic load on an elastic plate (Turcotte & Schubert, 1982). The elastic response of the footwall plate to this loading creates a depressed region (the *foredeep depozone*) closest to the load, as well as a subdued positive response (a *peripheral bulge*, or *forebulge*) at a distance from the load determined by the rigidity of the flexed crust. Distal from this peripheral bulge, an outer region of minor subsidence and sediment accumulation (the *back-bulge depozone*) may develop as a result of a secondary flexural depression and aggradation up to or above the forebulge crest.

The architecture of the Paradox basin-fill described here resembles other acknowledged foreland basins (Fig. 7). The tripartite Desmoinesian system corresponds in relative time and lithologic architecture with the foreland basin depozones of DeCelles & Giles (1996) and the 'underfilled trinity' of Sinclair (1997). In that interpretation, deposition of alluvial fan, fluvial megafan, and braidplain sediments in the proximal foredeep along the structural front of the Uncompahgre uplift is analogous to similar deposits reported by other workers in ancient and modern foreland basins (Willis, 1993; Sinha & Friend, 1994; DeCelles & Cavazza, 1999; Horton & DeCelles, 2001). The distribution of submarine evaporites in the medial foredeep of the Paradox Basin and these deposits' correlation with distal shallow-water carbonates is best described by a barred-basin evaporite model (Hite, 1970), and is consistent with foredeep deposition as recognized by Petrichenko *et al.* (1997) and Bukowski (1997). Finally, the synorogenic development of an uplift-parallel trend of comparatively thin platform carbonates on the distal basin margin is consistent with the model for foreland basin carbonates proposed by Dorobek (1995), and recognized in the Late Paleozoic foreland Tarim Basin (Allen *et al.*, 1999), the Huon Gulf basin (Galewsky *et al.*, 1996), the Alpine (Gupta & Allen, 2000), and Appalachian (Ver Straeten & Brett, 2000) foreland basins. Late-stage filling of remaining accommodation space by the mixed shallow water carbonates and redbeds of the Honaker Trail Formation and Lower Cutler Beds allowed overtopping of the basin by the terrestrial systems of the overlying Cutler Group. Decreased subsidence rates in the proximal basin and a large remaining sediment supply in the Uncompahgre highlands allowed subsequent widespread dispersal of arkosic Cutler Group sediment throughout the basin. This succession of a tripartite synorogenic deposystem overtopped by 'post-orogenic' siliciclastics suggests that the Paradox Basin experienced a late history common to many foreland basins (Heller *et al.*, 1988; Sinclair, 1997).

The Paradox Basin has been subject to syn- and post-orogenic structural and halokinetic deformation, as have many foreland basins. However, the structural style of deformation and its location on the relatively undeformed Colorado Plateau minimize these complications and provide rare insight into the development of ancient intraforeland flexural basins.

Shortening estimates from basement-involved uplifts are typically low (1s–10s of kilometers) in comparison to thin-skinned fold-thrust belts, even though both of these

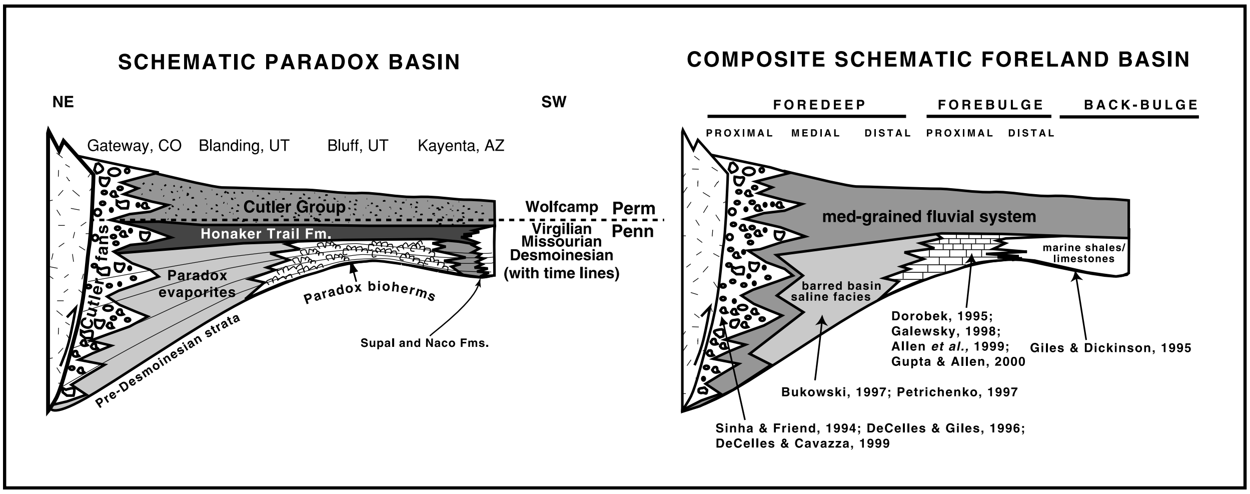

Fig. 7. (a) Schematic facies architecture of the Paradox Basin. (b) Schematic facies architecture of a composite restricted-marine isolated flexural basin. Facies recognized in other foreland basins are cited by reference.

structural systems have been shown to develop associated flexural basins (Hall & Chase, 1989; DeCelles & Giles, 1996). Given the subvertical nature of the uplift-bounding fault on the northeastern side of the Uncompahgre uplift and the lack of large subsidiary contractional structures outside of the Uncompahgre front, it is likely that the total shortening across the Uncompahgre-Paradox system is not much greater than the 10 km recorded by the basement overhang on the southwestern side of the uplift. This suggests that the 50-km wide Uncompahgre uplift load was largely non-migratory, especially in comparison to the 100s–1000s of kilometers load-migration values typical of large fold-thrust belts (DeCelles & Giles, 1996). Therefore, subsidence curves from individual locations (Lemke, 1985) do not display the upward-convex patterns characteristic of foreland basins that result from thin-skinned, migratory fold-thrust belts. However, the exponential decrease in subsidence magnitude away from the Uncompahgre uplift as recorded in Lemke's subsidence curves beckons further investigation of the distribution of differential subsidence. Moreover, the non-migratory nature of the thick-skinned Uncompahgre load eliminates the need to conduct complicated basin-fill restorations in order to restore the Paradox Basin to earlier states. This simplifies the procedure of flexural modeling described below.

Isopach (Wengerd, 1962), seismic (Frahme & Vaughn, 1983), surface geology (Hintze & Stokes, 1964), and borehole (White & Jacobson, 1983; this study) data have been compiled to construct a two-dimensional profile across the Uncompahgre–Paradox system (triangles: Figs 8 and 9). By choosing the top of the Missourian–Virgilian Honaker Trail Formation as a datum, stratigraphic units deformed by post-Pennsylvanian halokinetic and structural uplift were restored to their positions at the end of the Virgilian (Figs 8 and 9). The interface between the Paradox Formation (and its proximal Cutler Formation siliciclastic equivalents) and pre-Desmoinesian strata can then serve as a proxy for the basin's paleo-profile as localized subsidence waned in the Late Virgilian. The flexural equations of Turcotte & Schubert (1982) were applied to match a theoretical flexural profile to the actual basin profile of the Uncompahgre–Paradox system (Figs 8 and 9).

The Uncompahgre uplift was approximated with a series of rectangular loads according to compiled surface (Hintze & Stokes, 1964) and subsurface data (Frahme & Vaughn, 1983; White & Jacobson, 1983). Constrained by uplift-bounding faults on its south-west and north-east flanks, best estimates suggest that the Uncompahgre uplift was approximately 50-km wide, with preserved structural elevations varying between 3 and 5 km above the foreland footwall. Therefore, cross-sectional areas of ~200–220 km^2 are useful values for estimating the size of the Uncompahgre load. Reasonable average densities for the Uncompahgre range between 2600 and 2750 kg m^{-3} as it is composed mostly of granitic pegmatites and felsic metamorphic basement (Turcotte & Schubert, 1982). Using these dimensions and densities of the Uncompahgre uplift, the effective elastic thickness, continuity of the loaded plate (broken or unbroken), load density and basin-fill density were varied in attempts to replicate the existing basin-profile data. Reasonable elastic thicknesses for intracontinental lithosphere vary between 15 and 50 km, with corresponding flexural rigidities between 10^{22} and $10^{24.5}$ N m, assuming a Poisson's ratio of 0.25 and a Young's Modulus of 70 GPa (Beaumont, 1981; Turcotte & Schubert, 1982). Anorogenic and pre-orogenic continental crust, such as that within which the ARM developed, typically have elastic thicknesses in the 25–35 km range, which correspond to ~10^{23} N m flexural rigidities. The lithologies of sedimentary rocks that fill the Paradox Basin have densities between 2100 and 2550 kg m^{-3}.

The best-fit flexural model (Fig. 9) requires a rectangular load with a cross-sectional area of 214 km^2 and a density of 2670 kg m^{-3} flexing a fully broken continental plate with an effective elastic thickness of 25 km (flexural rigidity of ~10^{23} N m) and an average basin-fill density of 2325 kg m^{-3}. These values fall within the range of reasonable geological situations as discussed above. The requirement of a broken plate is supported by concepts of Laramide-style thick-skinned deformation as discussed by Erslev (1993), and suggests that the basin-bounding thrust fault may have completely broken through the crust.

DISCUSSION

As a foreland basin, the Paradox Basin presents a challenge to existing models for the ARM and our assumptions about the regional tectonic setting of intracontinental flexural basins. Foreland basins develop in convergent tectonic regimes in close proximity (~100–1000 km) to orogenic belts and have depositional axes approximately perpendicular to regional shortening directions. The NW–SE trends of the Paradox Basin flexural axis, the Uncompahgre uplift, and the trace of the Uncompahgre thrust suggest that the Uncompahgre–Paradox system developed as a result of shortening in a SW–NE direction. The lack of evidence for strike-slip offset along the flanks of the Paradox Basin, the Uncompahgre uplift (Mack & Rasmussen, 1984; Lindsey *et al.*, 1986) and other ARM basins and uplifts (Kluth & Coney, 1981; Budnik, 1986; B. Sralla, C. Saxon, and S. Decker, pers. comm.) further supports this interpretation. The fact that a number of other ARM uplift-basin pairs have orientations, structural styles and flexural signals similar to the Uncompahgre–Paradox system (Figs 1 and 3; Soegaard, 1990; Yang & Dorobek, 1995; Geslin, 1998; Gallardo & Blackwell, 1999; Barbeau, 2000; Hoy & Ridgway, 2002), calls into question models that ascribe development of the ARM solely to NW-directed convergence transmitted from the southern North American margin (e.g. Kluth & Coney, 1981).

Whereas structural and geodynamic evidence for crustal shortening in the ARM is strong, transpression cannot be

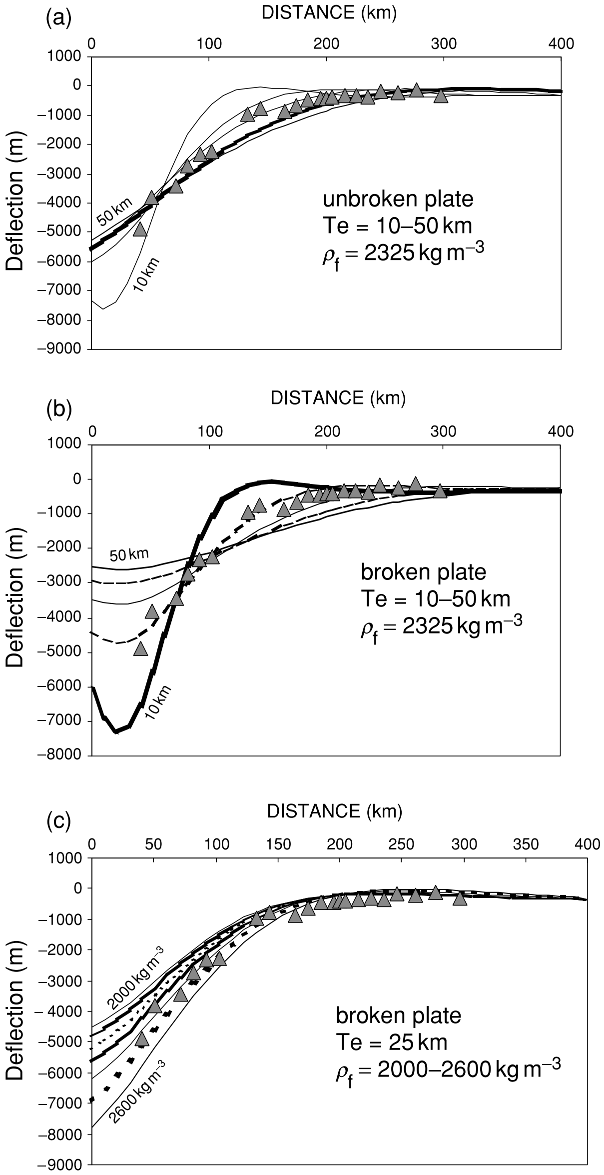

Fig. 8. Plots of modeling attempts. (a) Unbroken plate with effective elastic thicknesses varying between 10 and 50 km (b) Broken plate (at −30 km) with effective elastic thicknesses varying between 10 and 50 km (c) Broken plate (at −30 km) with effective elastic thickness of 25 km and varying basin-fill densities from 2000 to 2600 kg m^{-3}.

entirely ruled out. It is possible that widespread intracontinental transcurrent deformation could develop local contractional structures large enough to produce large flexural basins. However, given the widespread distribution of ARM uplifts and basins that show SW–NE and W–E shortening, models that better provide for those orientations of shortening should be carefully considered, at least until unambiguous evidence for through-going strike-slip offset is documented across the greater ARM region.

Two other orogenic systems have been compared with the ARM: the Late Cretaceous–Eocene Laramide orogeny of the western interior USA, and the intracontinental deformation associated with the Cenozoic collision of India and Asia. Both of these orogenic systems display widespread basement-involved deformation inboard from their respective active margins, and have been used as analogs for the ARM (Royden *et al.*, 1996; Kluth & Coney, 1981; Kluth, 1986; Ye *et al.*, 1996; Geslin, 1998). However, the driving mechanisms in neither of these orogens resemble tectonic processes recognized along the margins of Late Paleozoic North America.

Laramide structures are similar in size (40–80 km wide, 100 s of kilometers long) and structural style (basement-involved intracontinental thrusts) to ARM uplifts; in many cases Laramide fault slip actually reactivated ARM uplifts (DeVoto, 1980; Tweto, 1980). The large loads and small magnitudes of shortening (<10 km) associated with the Laramide uplifts produced adjacent flexural basins with non-migratory foreland basin depozones, which in many cases are similar in size and architecture to those of the Paradox Basin (Figs 3 and 7). Most of the Laramide uplifts and basins are orientated perpendicular to the E/NE-convergence direction of the shallowly dipping subducted plate that drove their development (Coney & Reynolds, 1977; Dickinson & Snyder, 1978; Constenius, 1996). In contrast, ARM uplifts and basins are elongated parallel to the expected shortening direction if indeed shortening was caused by stresses transmitted from the Ouachita-Marathon thrust belt. Thus, Royden *et al.* (1996) and Ye *et al.* (1996) proposed that Pennsylvanian–Permian NE-directed flat-slab subduction along the southwestern North American margin induced ARM

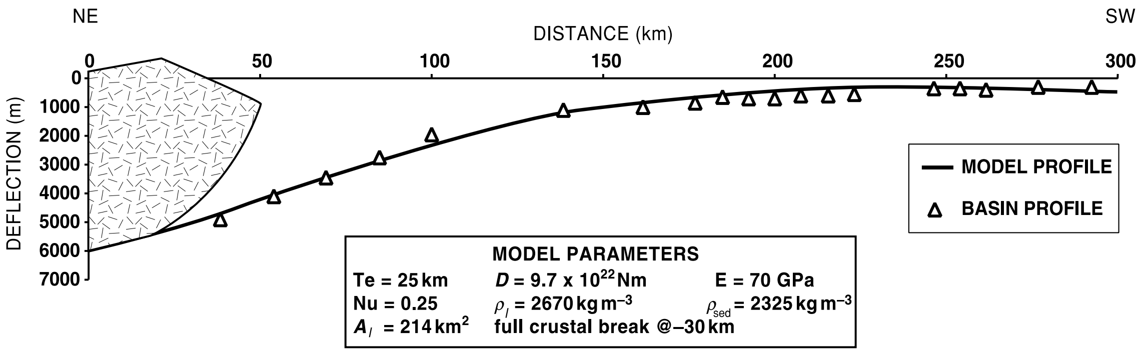

Fig. 9. Plot of restored basin and flexural model profiles along transect of the Paradox Basin. Nineteen wells used in the basin profile reconstruction are defined in Fig. 2. Modeling parameters are depicted in the inset and in the text.

shortening and uplift. Unfortunately, evidence for such a subduction system in the Late Paleozoic is sparse (Kluth, 1998; Dickinson & Lawton, 2001).

The widespread intracontinental deformation in central Asia associated with Himalayan orogenesis also beckons comparison with the ARM. Kluth & Coney (1981) and Kluth (1986) suggested that the NW-trending structures of the ARM resulted from lateral extrusion of crustal blocks as a Gondwanan promontory penetrated the southern margin of North America, in a fashion similar to the escape tectonic regime recognized in modern central Asia (e.g. Tapponnier *et al*., 2001). However, the central Asian analogue is not appropriate for the ARM for at least three reasons. First, hundreds of kilometers of strike-slip offset have been well documented along many uplift- and basin-bounding faults in central Asia, which is not the case in the ARM. Second, Cenozoic deformation in and around the Tibetan Plateau developed on the overriding Asian plate, whereas the ARM developed on the subducting plate. Third, deformation in central Asia has produced a regional, high-elevation plateau (the Tibetan Plateau) that is topographically and structurally distinct from the isolated basin and range paleotopography of the ARM. Perhaps a better analogy for the ARM would be the locally high topography generated by basement-involved thrusting in northern and central India (the Bundelkhand and Aravalli Ranges and the Shillong Plateau).

CONCLUSIONS

The Paradox Basin is an intracontinental flexural basin that developed under the load of the thrust-bounded ARM Uncompahgre uplift during Middle Pennsylvanian through early Permian time. The basin subsided rapidly during the Desmoinesian (~310–305 Ma), when uplift of the crystalline Uncompahgre block developed 2–5 km of accommodation space in the proximal basin and one-tenth of that on the distal margins. This large topographic load shed coarse granitic and arkosic sediment into the proximal basin, and spurred the rise of a peripheral forebulge, inducing deposition of thick evaporite-shale successions in the medial basin and growth of carbonate bioherms on the distal basin margins. The transitional Honaker Trail Formation filled remaining accommodation space in Missourian through Virgilian time (~305–295 Ma). The larger foreland basin system was then overtopped in the Wolfcampian (~295–260 Ma) by the complex terrestrial deposystems of the Cutler Group, which were no longer trapped by rapid subsidence in the proximal basin as they were during the Middle Pennsylvanian.

Loading of the Paradox Basin was accomplished by thrust displacement along parallel, oppositely dipping faults on either side of the 50-km wide NW–SE trending Uncompahgre uplift. The moderately NE-dipping Uncompahgre fault achieved ~10 km of shortening along the southwestern margin of the uplift, while faulting on the northeastern margin accommodated only minor shortening but equally great structural relief (~5 km) along a steeply dipping top-to-the northeast fault system. The resulting flexural wavelength suggests that at least one of these faults completely penetrates the elastic crust. Although transpression cannot be entirely ruled out, all available data suggest that the amount of strike-slip displacement along these faults is minimal, and that deformation is dominantly represented by NE–SW shortening.

The Paradox Basin's NW–SE orientation, thrust-bounded structural setting and foreland basin facies architecture are similar to many other ARM basins, and suggest that any model for the ARM tectonic event should provide a mechanism for localized NE–SW contraction and the development of intraforeland flexural basins.

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REFERENCES

Allen, M.B., Vincent, S.J. & Wheeler, P.J. (1999) Late Cenozoic tectonics of the Kepingtage thrust zone; interactions of the Tien Shan and Tarim Basin, Northwest China. *Tectonics*, **18**, 639–654.

Armin, R.A. (1987) Sedimentology and tectonic significance of Wolfcampian (Lower Permian) conglomerates in the Pedregosa Basin; southeastern Arizona, southwestern New Mexico, and northern Mexico. *Geol. Soc. Am. Bull.*, **99**, 42–65.

Aspler, L.B. & Donaldson, J.A. (1985) The Nonacho Basin (early Proterozoic), Northwest Territories, Canada; sedimentation and deformation in a strike-slip setting. In: *Strike-slip deformation, basin formation, and sedimantation* (Ed. by K.T. Biddle & N. Christie-Blick), pp. 193–209. SEPM (Society for Sedimentary Geology).

Aydin, A. & Nur, A. (1982) Evolution of pull-apart basins and their scale independence. *Tectonics*, **1**, 91–105.

Baars, D.L. (1961) Permian system of Colorado Plateau. *Am. Ass. Petrol. Geol. Bull.*, **46**, 149–218.

Baars, D.L. (1988) Triassic and older stratigraphy; Southern Rocky Mountains and Colorado Plateau. In: *Sedimentary cover; North American Craton* (Ed. by L. Sloss), pp. 53–64. Geol. Soc. Am.

Barbeau, D.L. (2000) Intraforeland flexure in the Ancestral Rocky Mountains. In: *Geological Society of America, 2000 Annual Meeting, Abstracts with Programs, Geol. Soc. Am.*, **32A**, 466.

Bartov, Y. (1979) *Israel geological map, scale 1:500 000*. Survey of Israel.

Beaumont, C. (1981) Foreland basins. *Geophys. J. Royal Astron. Soc.*, **65**, 291–329.

Ben-Avraham, Z., Garfunkel, Z., Almagor, G. & Hall, J.K. (1979) Continental breakup by a leaky transform; the Gulf of Elat (Aqaba). *Science*, **206**, 214–216.

Brewer, J.A., Good, R., Oliver, J.E., Brown, L.D. & Kaufman, S. (1983) COCORP profiling across the Southern Oklahoma Aulacogen; overthrusting of the Wichita Mountains and compression within the Anadarko Basin. *Geology*, **11**, 109–114.

Brown, R.D. (1970) Map showing recently active breaks along the San Andreas and related faults between the northern Gabilan Range and Cholame Valley, California, U.S. Geological Survey.

Budnik, R.T. (1986) Left-lateral intraplate deformation along the Ancestral Rocky Mountains; implications for Late Paleozoic plate motions. In: *Intraplate Deformation; Characteristics, Processes and Causes* (Ed. by B. Johnson & A. Bally), pp. 195–214. Elsevier.

Bukowski, K. (1997) Sedimentation of clastic strata associated with Miocene salts in Wieliczka (southern Poland). *Slov. Geol. Mag.*, **3**, 157–163.

Campbell, J.A. (1980) Lower Permian depositional systems and Wolfcampian paleogeography, Uncomphagre Basin, eastern Utah and southwestern Colorado. In: *Paleozoic Paleogeography of the West-Central United States; Rocky Mountain Paleogeography Symposium 1* (Ed. by T.D. Fouch & E.R. Magathan), pp. 327–340. Soc. Econ. Paleontol. Miner., Rocky Mount. Sect.

Christie-Blick, N. & Biddle, K.T. (1985) Deformation and basin formation along strike-slip faults. In: *Strike-slip deformation, basin formation, and sedimentation*. (Ed. by K.T. Biddle & N. Christie-Blick), pp. 1–34. SEPM (Society for Sedimentary Geology).

Condon, S.M. (1997) *Geology of the Pennsylvanian and Permian Cutler Group and Permian Kaibab Limestone in the Paradox Basin, Southeastern Utah and Southwestern Colorado.* US. Department of the Interior, US. Geological Survey, 46 pp.

Coney, P.J. & Reynolds, S.J. (1977) Cordilleran Benioff zones. *Nature*, **270**, 403–406.

Constenius, K.N. (1996) Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt. *Geol. Soc. Am. Bull.*, **108**, 20–39.

Cross, C.W. & Spencer, A.C. (1900) Geology of the Rico Mountains, Colorado. In: *United States Geological Survey Annual Report*, **21**, 15–165.

DeCelles, P.G. & Cavazza, W. (1999) A comparison of fluvial megafans in the Cordilleran (Upper Cretaceous) and modern Himalayan foreland basin systems. *Geol. Soc. Am. Bull.*, **111**, 1315–1334.

DeCelles, P.G., Gehrels, G.E., Quade, J., Ojha, T.P., Kapp, P.A. & Upreti, B.N. (1998) Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal. *Geol. Soc. Am. Bull.* **110**, 2–21.

DeCelles, P.G. & Giles, K.A. (1996) Foreland basin systems. *Basin Res.*, **8**, 105–123.

Devoto, R. (1980) Pennsylvanian stratigraphy and history of Colorado. In: *Colorado Geology* (Ed. by H.C. Kent & K.W. Porter), pp. 71–101. Ass. Geol., Rocky Mount.

Dickinson, W.R. & Lawton, T.F. (2001) Carboniferous to Cretaceous assembly and fragmentation of Mexico. *Geol. Soc. Am. Bull.*, **113**, 1142–1160.

Dickinson, W.R. & Snyder, W.S. (1978) Plate tectonics of the Laramide Orogeny. In: *Laramide Folding Associated with Basement Block Faulting in the Western United States* (Ed. by V. Matthews), *Memoir – Geol. Soc. Am.*, **151**, 355–366.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin E.R., McKittrick, M.A. & Olivares, M.D. (1988) Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region. *Geol. Soc. Am. Bull.* **100**, 1023–1039.

Dickinson, W.R., Soreghan, G.S. & Giles, K.A. (1994) Glacioeustatic origin of Permo-Carboniferous stratigraphic cycles; evidence from the southern Cordilleran foreland region. In: *Tectonic and Eustatic Controls on Sedimentary Cycles* (Ed. by J.M. Dennison & F.R. Ettensohn), pp. 25–34. SEPM (Society for Sedimentary Geology).

Diot, H. & Blaise, J. (1978) Etude structurale dans le precambrien et le paleozoique de la partie meridionale du domaine ligerien (Sud-Est du Massif Armoricain); Mauges, synclinal d'Ancenis et sillon houiller de la Basse-Loire. *Bulletin de la societe Geologique et Mineralogique de Bretagne*. Serie C **10**, 31–50.

Dorobek, S.L. (1995) Synorogenic carbonate platforms and reefs in foreland basins; controls on stratigraphic evolution and platform/reef morphology. In: *Stratigraphic Evolution of Foreland Basins* (Ed. by S.L. Dorobek & G.M. Ross), SEPM (Society for Sedimentary Geology), Tulsa, OK, United States. *Spec. Publ. – SEPM (Society for Sedimentary Geology*, **52**, pp. 127–147.

Eisbacher, G.H. (1985) Pericollisional strike-slip faults and synorogenic basins, Canadian Cordillera. In: *Strike-slip deformation, basin formation, and sedimentation* (Ed. by K.T. Biddle & N. Christie-Blick), pp. 265–282. SEPM (Society for Sedimentary Geology).

Elias, G.K. (1963) Habitat of Pennsylvanian algal bioherms, four corners area. In: *Shelf Carbonates of the Paradox Basin, a Symposium – Four Corners Geol. Soc., 4th Field Conference, 1963*, pp. 185–203.

Elston, D.P., Shoemaker, E.M. & Landis, E.R. (1962) Uncompahgre front and salt anticline region of Paradox Basin, Colorado and Utah. *Am. Ass. Petrol. Geol. Bull.*, **46**, 1857–1878.

Erslev, E.A. (1993) Thrusts, Back-Thrusts and Detachment of Rocky Mountain Foreland Arches. In: *Laramide Basement Deformation in the Rocky Mountain Foreland of the Western United States* (Ed. by C.J. Schmidt, R.B. Chase & E.A. Erslev), pp. 339–359. Geol. Soc. Am.

Frahme, C.W. & Vaughn, E.B. (1983) Paleozoic geology and seismic stratigraphy of the northern Uncompahgre Front, Grant County, Utah. In: *Rocky Mountain Foreland Basins and Uplifts* (Ed. by J.D. Lowell & R. Gries), pp. 201–211. Ass. Geol., Rocky Mount.

Franczyk, K.J., Clark, G., Brew, D.C. & Pitman, J.K. (1995) Chart showing lithology, mineralogy, and paleontology of the Pennsylvanian Hermosa Group at Hermosa Mountain, La Plata County, Colorado. US. Geological Survey, 18 pp., 1 sheet.

Freund, R., Zak, I. & Garfunkle, Z. (1968) Age and rate of the sinistral movement along the Dead Sea rift. *Nature*, **220**, 253–255.

Freund, R. (1971) *The Hope fault: a strike slip fault in New Zealand*. New Zealand Geological Survey, pp. **49**.

Galewsky, J., Silver, E.A., Gallup, C.D., Edwards, R.L. & Potts, D.C. (1996) Foredeep tectonics and carbonate platform dynamics in the Huon Gulf, Papua New Guinea. *Geology*, **24**, 819–822.

GALLARDO, J.D. & BLACKWELL, D.D. (1999) Thermal structure of the Anadarko Basin. *Am. Ass. Petrol. Geol. Bull.*, **83**, 333–361.

GE, H., JACKSON, M.P.A. & VENDEVILLE, B.C. (1997) Kinematics and dynamics of salt tectonics driven by progradation. *Am. Ass. Petrol. Geol. Bull.*, **81**, 398–423.

GESLIN, J.K. (1998) Distal ancestral Rocky Mountains tectonism; evolution of the Pennsylvanian-Permian Oquirrh-Wood River basin, southern Idaho. *Geol. Soc. Am. Bull.*, **110**, 644–663.

GOLDHAMMER, R.K., OSWALD, E.J. & DUNN, P.A. (1994) High-frequency, glacio-eustatic cyclicity in the Middle Pennsylvanian of the Paradox Basin; an evaluation of Milankovitch forcing. In: *Orbital Forcing and Cyclic Sequences* (Ed. by B.P.L. De & D.G. Smith), *Spec. Publ. Int. Ass. Sed.*, **19**, pp. 243–283. Blackwell.

GRAHAM, S.A., DICKINSON, W.R. & INGERSOLL, R.V. (1975) Himalayan-Bengal model for flysch dispersal in the Appalachian–Ouachita system. *Geol. Soc. Am. Bull.*, **86**, 273–286.

GUINEBERTEAU, B., BOUCHEZ, J.L. & VIGNERESSE, J.L. (1987) The Mortagne granite pluton (France) emplaced by pull-apart along a shear zone; structural and gravimetric arguments and regional implication. *Geol. Soc. Am. Bull.*, **99**, 763–770.

GUIRAUD, M. & SEGURET, M. (1985) A releasing solitary overstep model for the Late Jurassic-Early Cretaceous (Wealdian) Soria strike-slip basin (northern Spain). In: *Strike-slip deformation, basin formation, and sedimentaion*. (Ed. by K.T. Biddle & N. Christie-Blick), pp. 159–175. SEPM (Society for Sedimentary Geology).

GUPTA, S. & ALLEN, P.A. (2000) Implications of foreland paleotopography for stratigraphic development in the Eocene distal Alpine foreland basin. *Geol. Soc. Am. Bull.*, **112**, 515–530.

HAGEN, E.S., SHUSTER, M.W. & FURLONG, K.P. (1985) Tectonic loading and subsidence of intermontane basins; Wyoming foreland province. *Geology*, **13**, 585–588.

HALL, M.K. & CHASE, C.G. (1989) Uplift, unbuckling, and collapse; flexural history and isostasy of the Wind River Range and Granite Mountains, Wyoming. *J. Geophys. Res.*, **94**, 17 581–17 593.

HELLER, P.L., ANGEVINE, C.L., WINSLOW, N.S. & PAOLA, C. (1988) Two-phase stratigraphic model of foreland-basin sequences. *Geology*, **16**, 501–504.

HINTZE, L.F. & STOKES, W.L. (1964) *Geologic Map of Southeastern Utah.*

HITE, R.J. (1960) Stratigraphy of the facies of the Paradox member of the Hermosa Formation of southeastern Utah and southwestern Colorado. In: *Geology of the Paradox Basin Fold and Fault Belt, 3d Field Conference, Guidebook*, pp. 86–89. Four Corn. Geol. Soc.

HITE, R.J. (1970) Shelf carbonate sedimentation controlled by salinity in the Paradox Basin, Southeast Utah. In: *Third Symposium on Salt*, In: *Stratigraphy-sedimentation, geochemistry, tectonics, solution mining, underground storage-disposal* (Ed. by J.L. Rau & L.F. Dellwig), **1**, pp. 48–66. N. Ohio Geol. Soc.

HORTON, B.K. & DECELLES, P.G. (2001) Modern and ancient fluvial megafans in the foreland basin system of the central Andes, southern Bolivia: implications for drainage network evolution in fold-thrust belts. *Basin Res.*, **13**, 43–63.

HOY, R.G. & RIDGWAY, K.D. (2002) Syndepositional thrust-related deformation and sedimentation in an Ancestral Rocky Mountains basin, Central Colorado trough, Colorado, USA *Geol. Soc. Am. Bull.*, **114**, 804–828.

JACKSON, M.P.A., SCHULTZ, E.D.D., HUDEC, M.R., WATSON, I.A. & PORTER, M.L. (1998) Structure and evolution of Upheaval Dome; a pinched-off salt diapir. *Geol. Soc. Am. Bull.*, **110**, 1547–1573.

JOHNSON, C.E. & HADLEY, D.M. (1976) Tectonic implications of the Brawley earthquake swarm, Imperial Valley, California, January 1975. *Bull. Seism. Soc. Am.*, **66**, *Spec. Papers on the Brawley, Calif. Earthquakes of Jan. 1975*), pp. 1133–1144.

KELLEY, V.C. (1955) Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium. 120 pp. University of New Mexico Press.

KETIN, I. (1969) Ueber die nordanatolische Horizontalverschiebung. *Bull. Min. Res. Expl. Inst. Turkey*, **72**, 1–28.

KING, P.B. & EDMONSTON, G.J. (1972) Generalized tectonic map of North America. US. Geological Survey. 1 sheet.

KING, P.B. (1975) The Ouachita and Appalachian orogenic belts. In: *The Gulf of Mexico and the caribbean*. (Ed. by E. Nairn & M. Stehli), 201–241. Plenum.

KLUTH, C.F. (1986) Plate tectonics of the ancestral Rocky Mountains. In: *Paleotectonics and Sedimentation in the Rocky Mountain Region, United States* (Ed. by J.A. Peterson), **41**, pp. 353–369. Am. Ass. Petrol. Geol.

KLUTH, C.F. (1998) Late Paleozoic deformation of interior North America; the greater Ancestral Rocky Mountains; discussion. *Am. Ass. Petrol. Geol. Bull.*, **82**, 2272–2279.

KLUTH, C.F. & CONEY, P.J. (1981) Plate tectonics of the ancestral Rocky Mountains. *Geology*, **9**, 10–15.

LEMKE, L. (1985) *Subsidence Analysis of the Paradox Basin, Utah*. MSc Thesis, University of Arizona, Tucson, AZ.

LINDSEY, D.A., CLARK, R.F. & SOULLIERE, S.J. (1986) Minturn and Sangre de Cristo formations of southern Colorado; a prograding fan delta and alluvial fan sequence shed from the Ancestral Rocky Mountains. In: *Paleotectonics and Sedimentation in the Rocky Mountain Region, United States* (Ed. by J.A. Peterson), **41**, pp. 541–561, Am. Ass. Petrol. Geol.

LOOPE, D.B., SANDERSON, G.A. & VERVILLE, G.J. (1990) Abandonment of the name 'Elephant Canyon Formation' in southeastern Utah; physical and temporal implications. *Mount. Geol.*, **27**, 119–130.

MACK, G.H. & RASMUSSEN, K.A. (1984) Alluvial-fan sedimentation of the Cutler Formation (Permo–Pennsylvanian), near Gateway, Colorado. *Geol. Soc. Am. Bull.*, **95**, 109–116.

MALLORY, W.W. (1958) Pennsylvanian coarse arkosic redbeds and associated mountains in Colorado. In: *Symposium on Pennsylvanian Rocks of Colorado and Adjacent Areas*, pp. 17–20. Ass. Geol., Rocky Mount.

MANSPEIZER, W. (1985) The Dead Sea Rift: impact of climate and tectonism on Pleistocene and Holocene sedimentation. In: *Strike-slip deformation, basin formation, and sedimentation*. (Ed. by K.T. Biddle & N. Christie-Blick), pp. 143–158. SEPM (Society for Sedimentary Geology) .

MCKENZIE, D. (1978) Some remarks on the development of sedimentary basins. *Earth Plan. Sci. Let.*, **40**, 25–32.

MURPHY, K. (1987) Eclian origin of upper Paleozoic red siltstones at Mexican Hat and Dark Canyon, southeastern Utah. MSc thesis, University of Nebraska, Lincoln.

NILSEN, T.H. & MCLAUGHLIN, R.J. (1985) Comparison of tectonic framework and depositional patterns of the Hornelen strike-slip basin of Norway and the Ridge and Little Sulphur Creek strike-slip basins of California. In: *Strike-slip deformation, basin formation, and sedimentation* (Ed. by K.T. Biddle &

N. Christie-Blick), pp. 79–103. SEPM (Society for Sedimentary Geology) .

Ohlen, H.R. & McIntyre, L.B. (1965) Stratigraphy and tectonic features of Paradox Basin, four corners area. *Am. Ass. Petrol. Geol. Bull.*, **49,** 2020–2040.

Peterson, J.A. & Hite, R.J. (1969) Pennsylvanian evaporite-carbonate cycles and their relation to petroleum occurrence, southern Rocky Mountains. In: *Evaporites and Petroleum*, **53**, pp. 884–908. Am. Ass. Petrol. Geol.

Peterson, J.A. & Ohlen, H.R. (1963) Pennsylvanian shelf carbonates, Paradox Basin. In: *Shelf Carbonates of the Paradox Basin, a Symposium – Four Corners Geol. Soc., 4th Field Conference*, pp. 65–79.

Petrichenko, O.I., Peryt, T.M. & Poberegsky, A.V. (1997) Peculiarities of gypsum sedimentation in the Middle Miocene Badenian evaporite basin of Carpathian Foredeep. *Slov. Geol. Mag.*, **3,** 91–104.

Pitman, W.C., III & Andrews, J.A. (1985) Subsidence and thermal history of small pull-apart basins. In: *Strike-Slip Deformation, Basin Formation, and Sedimentation* (Ed. by K.T. Biddle & B.N. Christie). *Spec. Publ. – Soc. Econ. Paleont. Miner.*, **37**, pp. 45–119. SEPM (Society for Sedimentary Geology).

Pray, L.C. & Wray, J.L. (1963) Porous algal facies (Pennsylvanian), Honaker Trail, San Juan Canyon, Utah. In: *Shelf Carbonates of the Paradox Basin, a Symposium – Four Corners Geol. Soc., 4th Field Conference*, pp. 204–234.

Ross, C.A. (1979) Late Paleozoic collision of North and South America. *Geology*, **7,** 41–44.

Royden, L.H. (1985) The Vienna Basin: a thin-skinned pull-apart basin. In: *Strike-slip deformation, basin formation, and sedimentation*, (Ed. by K.T. Biddle & N. Christie-Blick), pp. 319–338. SEPM (Society for Sedimentary Geology).

Royden, L.H., Burchfiel, B.C. & Schuepbach, M. (1996) Late Paleozoic deformation of the Ancestral Rocky Mountains; result of an Andean margin along southwestern North America? In: *Geological Society of America, 28th Annual Meeting – Abstracts with Programs*, pp. 270. Geol. Soc. Am.

Schubert, C. & Laredo, M. (1979) Late Pleistocene and Holocene faulting in Lake Valencia Basin, North-central Venezuela. *Geology*, **7**, 289–292.

Schubert, C. (1980) Late-Cenozoic pull-apart basins, Bocono fault zone, Venezuelan Andes. *Journ. Struct. Geol.*, 2463–468.

Schwartz, D.P., Cluff, L.S. & Donnelly, T.W. (1979) Quaternary faulting along the Caribbean-North American plate boundary in Central America. In: *Recent crustal movements, 1977*. (Ed. by A. Whitten, E. Green & R. Meade), pp. 431–445. Elsevier.

Sharp, R.V. (1975) En echelon fault patterns of the San Jacinto Fault zone. *Spec. Rep. California Div. Mines Geol.*, **118**, 147–152.

Shoemaker, E.M., Case, J.E. & Elston, D.P. (1958) Salt anticlines of the Paradox Basin. In: *Guidebook to the Geology of the Paradox Basin, 9th Annual Field Conference*, pp. 39–59. Intermt. Ass. Pet. Geol.

Shultz, A.W. (1984) Subaerial debris-flow deposition in the upper Paleozoic Cutler Formation, western Colorado. *Journ. Sed. Petr.*, **54**, 758–772.

Sinclair, H.D. (1997) Tectonostratigraphic model for underfilled peripheral foreland basins; an Alpine perspective. *Geol. Soc. Am. Bull.*, **109**, 324–346.

Sinha, R. & Friend, P.F. (1994) River systems and their sediment flux, Indo-Gangetic plains, northern Bihar, India. *Sedimentology*, **41,** 825–845.

Sloss, L.L. (1988) Tectonic evolution of the craton in Phanerozoic time. In: *Sedimentary cover, North American Craton* (Ed. by L. Sloss), pp: 25–51. Geol. Soc. Am.

Soegaard, K. (1990) Fan-delta and braid-delta systems in Pennsylvanian Sandia Formation, Taos Trough, northern New Mexico; depositional and tectonic implications. *Geol. Soc. Am. Bull.*, **102,** 1325–1343.

Soreghan, G.S. (1994) Stratigraphic responses to geologic processes; Late Pennsylvanian eustasy and tectonics in the Pedregosa and Orogrande basins, ancestral Rocky Mountains. *Geol. Soc. Am. Bull.*, **106,** 1195–1211.

Steel, R., Gjelberg, J., , Helland, H.W., , Kleinspehn, K., Nottvedt, A. & Rye, L.M. (1985) The Tertiary strike-slip basins and orogenic belt of Spitsbergen. In: *Strike-slip deformation, basin formation, and sedimentation* (Ed. by K.T. Biddle & N. Christie-Blick), pp. 339–359. SEPM (Society for Sedimentary Geology).

Stevenson, G.M. & Baars, D.L. (1986) The Paradox; a pull-apart basin of Pennsylvanian age. In: *Paleotectonics and Sedimentation in the Rocky Mountain Region, United States* (Ed. by J.A. Peterson), **41**, pp. 513–539. Am. Ass. Petrol. Geol.

Szabo, E. & Wengerd, S.A. (1975) Stratigraphy and tectogenesis of the Paradox Basin. *Field Symp – Guidebook Four Corners Geol Society*, **8,** 193–210.

Tapponnier, P., Xu, Z., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G. & Yang, J. (2001) Oblique stepwise rise and growth of the Tibet Plateau. *Science*, **294** (5547), 1671–1677.

Tidwell, W.D. (1998) A new Upper Pennsylvanian or Lower Permian flora from southeastern Utah: *Brigham Young University Geology Studies*, **35**, 33–56.

Thomas, W.A. (1998) Black Warrior Basin. In: *Sedimentary cover; North American Craton* (Ed. by L. Sloss), pp. 1 sheet. Geol. Soc. Am.

Turcotte, D.L. & Schubert, G. (1982) *Geodynamics: Applications of Continuum Physics to Geological Problems*. Wiley.

Tweto, O. (1980) Summary of Laramide orogeny in Colorado. In: *Colorado Geology* (Ed. by H.C. Kent & K.W. Porter) pp. 129–134. Ass. Geol., Rocky Mount.

Ver Straeten, C.A. & Brett, C.E. (2000) Bulge migration and pinnacle reef development, Devonian Appalachian foreland basin. *J. Geol.*, **108,** 339–352.

Waechter, N.B. & Johnson, W.E. (1986) Pennsylvanian-Permian paleostructure and stratigraphy as interpreted from seismic data in the Piceance Basin, Northwest Colorado. In: *New Interpretations of Northwest Colorado Geology* (Ed. by D.S. Stone & K. Johnson), pp. 51–64. Ass. Geol., Rocky Mount.

Welsh, J.E. (1958) Faunizones of the Pennsylvanian and Permian rocks in the Paradox Basin [Colorado Plateau]. In: *Guidebook to the Geology of the Paradox Basin, 9th Annual Field Conference*, pp. 153–162. Intermount. Ass. Petrol. Geol.

Wengerd, S.A. (1962) Pennsylvanian sedimentation in Paradox Basin, Four Corners region. In: *Pennsylvanian System in the United States – A Symposium*, pp. 264–330.

Wengerd, S.A. & Matheny, M.L. (1958) Pennsylvanian system of Four Corners Region. *Am. Ass. Petrol. Geol. Bull.*, **42,** 2048–2106.

White, M.A. & Jacobson, M.I. (1983) Structures associated with the southwest margin of the ancestral Uncompahgre Uplift.

In: *Northern Paradox Basin-Uncompahgre Uplift* (Ed. by W.R. Averett), pp. 33–39. Grand Junction Geol. Soc.

Willis, B. (1993) Evolution of Miocene fluvial systems in the Himalayan foredeep through a two kilometer-thick succession in northern Pakistan. *Sedimentary Geol.*, **88**, 77–121.

Yang, K.M. & Dorobek, S.L. (1995) The Permian Basin of West Texas and New Mexico; flexural modeling and evidence for lithospheric heterogeneity across the Marathon foreland. In: *Stratigraphic Evolution of Foreland Basins* (Ed. by S.L. Dorobek & G.M. Ross), *Spec. Publ. – SEPM* (*Soc. Sedimentary Geol.*), **52**, pp. 37–50. SEPM (Society for Sedimentary Geology), Tulsa, OK, United States.

Ye, H., Royden, L., Burchfiel, C. & Schuepbach, M. (1996) Late Paleozoic deformation of interior North America; the greater ancestral Rocky Mountains. *Am. Ass. Petrol. Geol. Bull.*, **80**, 1397–1432.

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