Tectonic control on coarse-grained foreland-basin sequences: An example from the Cordilleran foreland basin, Utah

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ABSTRACT

Newly released reflection seismic and borehole data, combined with sedimentological, provenance, and biostratigraphic data from Upper Cretaceous–Paleocene strata in the proximal part of the Cordilleran foreland-basin system in Utah, establish the nature of tectonic controls on stratigraphic sequences in the proximal to distal foreland basin. During Campanian time, coarse-grained sand and gravel were derived from the internally shortening Charleston-Nebo salient of the Sevier thrust belt. A rapid, regional Campanian progradational event in the distal foreland basin (>200 km from the thrust belt in <8 m.y.) can be tied directly to active thrust-generated growth structures and an influx of quartzose detritus derived from the Charleston-Nebo salient. Eustatic sea-level variation exerted a minimal role in sequence progradation.

Keywords: sequence stratigraphy, foreland basins, fold and thrust belts, progradation, Book Cliffs, Utah.

INTRODUCTION

Several controversies have emerged in foreland-basin stratigraphy since the mid-1980s, and two key questions are at the heart of these debates. (1) Does coarse-grained detritus reflect intensified tectonic activity in the adjacent fold-thrust belt, or is it a signature of postthrusting isostatic adjustment (e.g., Heller et al., 1988; Burbank et al., 1988; Garcia-Castellanos, 2002)? (2) Is tectonics or eustasy the principal control on sequence stacking patterns (e.g., Van Wagoner, 1995; Yoshida et al., 1996; Robinson and Slingerland, 1998; Houston et al., 2000)? Answers to these questions are found where distal foreland-basin sediments can be traced into proximal coarse-grained sediments in thrust-generated growth structures. Both questions are fundamental to stratigraphic applications in tectonic and eustatic problems.

One of the world's premier natural laboratories for the study of foreland-basin sequence stratigraphy and the relationship between tectonics and coarse-grained sediment flux is exposed in the Book Cliffs of eastern Utah (Fig. 1). In a single outcrop belt, Upper Cretaceous–Paleocene piedmont fluvial deposits near the front of the Sevier thrust belt can be tracked east-southeastward into coastal plain, deltaic, and shallow-marine facies over a distance of >200 km. The Upper Cretaceous section is replete with regional-scale erosion surfaces interpreted by some as sequence-bounding unconformities (e.g., Van Wagoner, 1995). This paper focuses on a coarse-grained sandstone unit, the middle to upper Campanian Castlegate Sandstone, that overlies one of the major erosion surfaces. Over a distance of ~240 km, the Castlegate Sandstone can be traced from an ~200-m-thick conglomeratic fluvial sandstone into a fine-grained marginal- to shallow-marine sandstone and siltstone unit only a few meters thick. Partly because of its great distance of eastward progradation, the Castlegate Sandstone has become a focal point of the controversy over tectonic vs. eustatic controls on foreland sequences (e.g., Van Wagoner, 1995; Yoshida et al., 1996; Robinson and Slingerland, 1998; Miall and Arush, 2001). In addition, because the Sevier thrust belt was active contemporaneously with Castlegate deposition (e.g., DeCelles et al., 1995), the Book Cliffs provide an excellent proving ground for the debate about the significance of coarse-grained sediments in foreland basins.

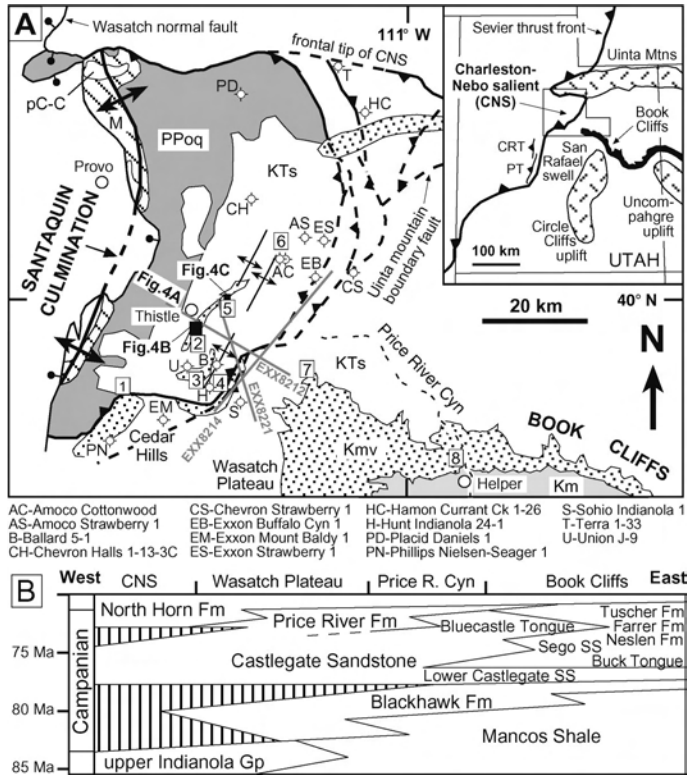

Figure 1. A: Map of Charleston-Nebo salient and northernmost Book Cliffs showing rock units, thrust faults (dashed where buried), key seismic coverage (gray lines), measured stratigraphic sections (1–7; 8 is location of additional Blackhawk sandstone samples), and wells. Rock units: KTs—Cretaceous–Tertiary strata (North Horn and younger formations), Kmv—Cretaceous Mesaverde Group (Blackhawk, Castlegate, and Price River Formations; dot pattern), Km—Cretaceous Mancos Shale, PPoq—Pennsylvanian–Permian Oquirrh Group, M—Mississippian, pC–C—Precambrian–Cambrian. Inset map shows Sevier thrust front, Laramide basement uplifts, and Canyon Range (CRT) and Pavant thrusts (PT). B: Chronostratigraphic chart for Campanian–Maastrichtian deposits across central Utah, modified from Robinson and Slingerland (1998). Vertical ruled pattern denotes nondepositional or erosional hiatus.

Resolution of the questions mentioned here has been hindered by the fact that the most proximal Upper Cretaceous–Paleocene facies in the frontal Sevier belt have not been correlated accurately with distal foreland-basin deposits in the Book Cliffs. We present previously unreleased seismic reflection and borehole data and new sedimentological, provenance, and palynological data from this proximal facies belt. The subsurface data provide the crucial information needed to tie distal fluvial deposits into coeval coarse-grained proximal alluvial-fan facies. We show that Castlegate progradation was coeval with major crustal shortening within the Charleston-Nebo salient of the Sevier belt. The base-Castlegate unconformity may be attributed to a combination of thrust-generated uplift in the proximal basin and reduced accommodation in the distal foreland owing to incipient Laramide intraforeland uplift.

GEOLOGIC SETTING

The Sevier thrust belt in north-central Utah forms the eastward-convex Charleston-Nebo salient, consisting of the Charleston and Nebo thrusts, a large antiformal duplex (the Santaquin culmination), and a frontal set of imbricate thrusts and triangle zone (Constenius, 1998). The Charleston-Nebo salient is distinguished by a thick Pennsylvanian–Permian (Oquirrh Group) section. The adjacent foreland basin contains a record of Sevier deformation exposed along a proximal-to-distal transect from central Utah to western Colorado (Fig. 1). In the proximal sector, a wedge-top depozone up to 2 km thick buries the leading edge of the Charleston-Nebo salient, and Tertiary extensional deformation partially obscures the thrust relationships (Constenius, 1998). Therefore, subsurface information is required for delineation of crosscutting and growth stratal relationships among foreland-basin units and thrust structures.

STRATIGRAPHY AND SEDIMENTOLOGY

Lithostratigraphic and chronostratigraphic data from measured sections (Fig. 2)[1] and ~50 newly released seismic reflection profiles and ~15 wells (including dip-meter, sample, and sonic logs) help to define relationships along an east-west profile across the Charleston-Nebo salient. Seven new palynological assemblages (summarized in Fig. 2, see footnote one) facilitate lateral correlations and confirm age assessments for the following stratigraphic units (Fig. 1B): (1) The upper Albian–lower Campanian Indianola Group consists of an upward-coarsening, 1–4-km-thick succession of alluvial-fan and fluvial sandstone and conglomerate with thin (<100 m) intervals of well-sorted shallow-marine sandstone and shale. (2) The lower Campanian Blackhawk Formation contains up to 1 km of fluvial, deltaic, and shallow-marine sandstone and siltstone. (3) The middle to upper Campanian Castlegate Sandstone and Price River Formation are each ~200 m thick and consist of fluvial sandstone and minor siltstone. (4) The Maastrichtian–Paleocene North Horn Formation consists of 100–600 m of alluvial-fan, fluvial, and lacustrine conglomerate, sandstone, siltstone, and limestone.

The preceding depositional interpretations and our new stratigraphic correlations (Fig. 2) supplement previous work on the Indianola Group, Mesaverde Group (Blackhawk, Castlegate, and Price River Formations), and North Horn Formation (Walton, 1944; Spieker, 1946; Pinnell, 1972; Jefferson, 1982; Lawton, 1982, 1983, 1986; Fouch et al., 1983; Robinson and Slingerland, 1998). One notable advance entails correlation of a white, quartzite-clast, cobble-boulder conglomerate that crops out in the Charleston-Nebo salient (Fig. 2) and the Campanian Castlegate–Price River succession of the northern Book Cliffs. This correlation is supported by tracing of seismic reflections tied to outcrop and well control by using synthetic seismograms and lithologic logs from the Sohio Indianola 1 well (Fig. 1A). This well penetrated ~280 m of white sandstone and conglomerate that contrast sharply with an overlying ~380-m-thick interval of gray-brown siltstone, sandstone, and interbedded limestone, and an underlying >800-m-thick interval of gray-tan siltstone and mudstone. We interpret this section as Castlegate–Price River strata sandwiched between North Horn and Blackhawk strata, consistent with the lithology and thickness of corresponding units from nearby localities (sections 4 and 7, Fig. 2). Our correlations agree with those of Spieker (1946) and Pinnell (1972) in that Castlegate and Price River deposits of Price River Canyon become indistinguishable to the west near Thistle (Fig. 1). We note, however, the presence of a lower conglomeratic interval and upper sandy interval in several sections (sections 3, 4, and 7, Fig. 2) that may approximate the Castlegate and Price River Formations, respectively.

The most significant vertical stratigraphic change is an abrupt upsection increase in proximal facies at the Blackhawk-Castlegate unconformity. The regional extent of this facies transition across the Charleston-Nebo salient and Book Cliffs (Figs. 1 and 2) requires >200 km of eastward progradation of the middle to late Campanian Castlegate fluvial system (Spieker, 1946; Van Wagoner, 1995).

SEDIMENT PROVENANCE

Paleocurrent data, conglomerate clast counts, and sandstone petrographic data from the foreland-basin deposits (Fig. 2) constrain the erosional history of the Charleston-Nebo salient. Provenance data (Fig. 3) (Appendix DR1, Tables DR1 and DR2[2]) fall into three categories. (1) Indianola and Blackhawk strata contain Precambrian–Mesozoic clasts and sublitharenitic sandstone composed of monocrystalline quartz (Qm), lithic fragments (Lt), and limited feldspar (F). Paleocurrent data indicate southeastward transport. Given the presence of Precambrian clasts, a part of the Indianola–Blackhawk succession must have been derived from the Midas and Sheeprock thrust sheets, originally 10–100 km west of the Charleston-Nebo salient (Mitra, 1997). (2) Castlegate–Price River conglomerates are dominated by quartzite and quartzose-sandstone clasts derived from the Pennsylvanian–Permian Oquirrh Group, and sandstone compositions are dominated by monocrystalline quartz. Paleocurrent data indicate transport toward the east-southeast. These data are consistent with previous petrographic studies in the Book Cliffs (Lawton, 1983; Franczyk et al., 1990; Franczyk and Pitman, 1991), although Miall and Arush (2001) identified more feldspar (Fig. 3C). We attribute these deposits to erosion of the sandstone- and quartzite-dominated upper part of the 4–8-km-thick Oquirrh Group that composes the roof thrust sheet of the Santaquin culmination (Fig. 1). (3) North Horn conglomerates contain a mix of Precambrian and Paleozoic clasts. Paleocurrent directions are variable, ranging from eastward to southward. Elevated amounts of chert clasts are consistent with petrographic trends described by Lawton (1983) in the uppermost Cretaceous section in the Book Cliffs.

The most intriguing aspect of our petrographic data is the abrupt Campanian appearance of quartzite clasts, quartzose-sandstone clasts, and quartzose sand derived from the Oquirrh Group (Fig. 3). In citing possible sources of Castlegate–Price River sediment, previous workers have called on Precambrian rocks of the Canyon Range and Pavant thrust sheets (Fig. 1) ~150 km west-southwest of the Book Cliffs (e.g., Van Wagoner, 1995; Robinson and Slingerland, 1998). However, the southeastward paleocurrent data, abundance of Oquirrh clasts, and highly quartzose sandstone compositions consistently implicate the Charleston-Nebo salient, and specifically the roof of the Santaquin culmination, as the main sediment source. This relationship is consistent with Campanian duplexing beneath the crest of the evolving Santaquin culmination; shortening within the duplex generated >20 km of structural relief as a result of >70 km of eastward translation along the kinematically linked Charleston-Nebo thrust system (Constenius, 1998). Furthermore, flexural processes governing accommodation in the Book Cliffs may be linked to loading by the more proximal

[1]Loose insert: Figure 2. Measured sections from Upper Cretaceous–lower Tertiary proximal foreland basin, including lithologies, stratigraphic correlations, paleocurrent data, clast compositional data, and locations of palynological and sandstone petrographic samples.

[2]GSA Data Repository item 2004102, Appendix DR1, provenance methods, Appendix DR2, seismic parameters, and Tables DR1 and DR2, point-count data, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

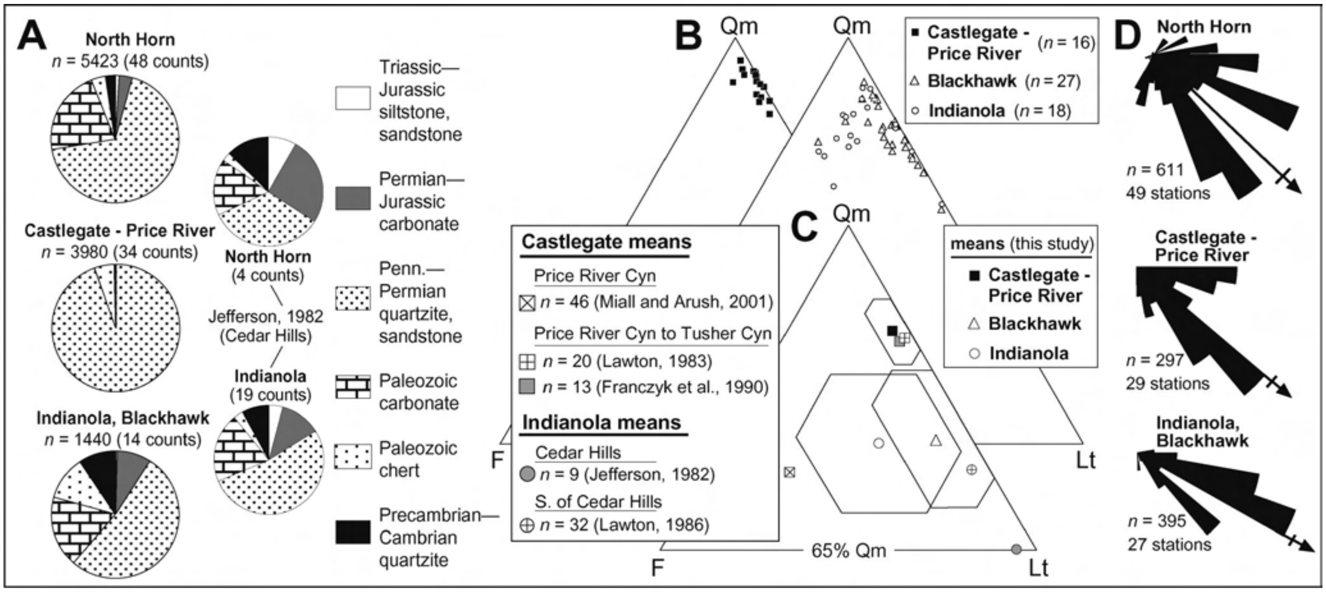

Figure 3. Provenance data from measured stratigraphic sections and additional localities in Charleston-Nebo salient. A: Clast compositional data. B: Qm-F-Lt plot (see footnote 2 in text) of all sandstone petrographic data. C: Means (geometric symbols) and standard deviations (polygons) of data plotted in B. Castlegate means from previous studies are shown for comparison. D: Rose diagrams showing all paleocurrent data, including vector means (arrows) and 95% confidence intervals (short arc lines).

Charleston-Nebo system rather than by the commonly cited Canyon Range and Pavant thrusts farther to the west-southwest (e.g., Houston et al., 2000; Miall and Arush, 2001).

PROXIMAL BASIN GEOMETRY

Seismic reflection lines (Appendix DR2; see footnote 2) reveal the buried frontal tip of the Charleston-Nebo thrust, growth strata in the interior of the thrust sheet, and angular unconformities at the base of the proximal Blackhawk and North Horn Formations. The blind frontal tip of the Charleston-Nebo thrust and the Indianola strata in its footwall are erosionally truncated and overlapped by subhorizontal reflectors of the Blackhawk Formation (Fig. 4A). This relationship indicates cessation of slip at the frontal fault tip by Campanian time. However, pronounced westward thinning coupled with an upsection decrease in reflector dip in Blackhawk through lower North Horn strata on the eastern flank of the Oil Hollow anticline (Fig. 4A) require deposition synchronous with continued Campanian–Maastrichtian deformation and fold-limb rotation in the interior of the Charleston-Nebo salient. Campanian time thus marks an important transition in the salient from thrust-front–concentrated deformation to internal shortening. In westernmost localities, the North Horn Formation overlaps folded and erosionally beveled Paleozoic–Mesozoic rocks (Fig. 4A; section 1, Fig. 2; Spieker, 1946; Pinnell, 1972; Jefferson, 1982).

Surface mapping substantiates the seismically imaged growth-strata relationships. At Dry Hollow (Fig. 4B), steeply east dipping Castlegate–Price River conglomerate overlies in angular unconformity the subvertical marine sandstone of the Indianola Group (correlated with the Turonian–Coniacian lower Funk Valley Formation; Lawton,

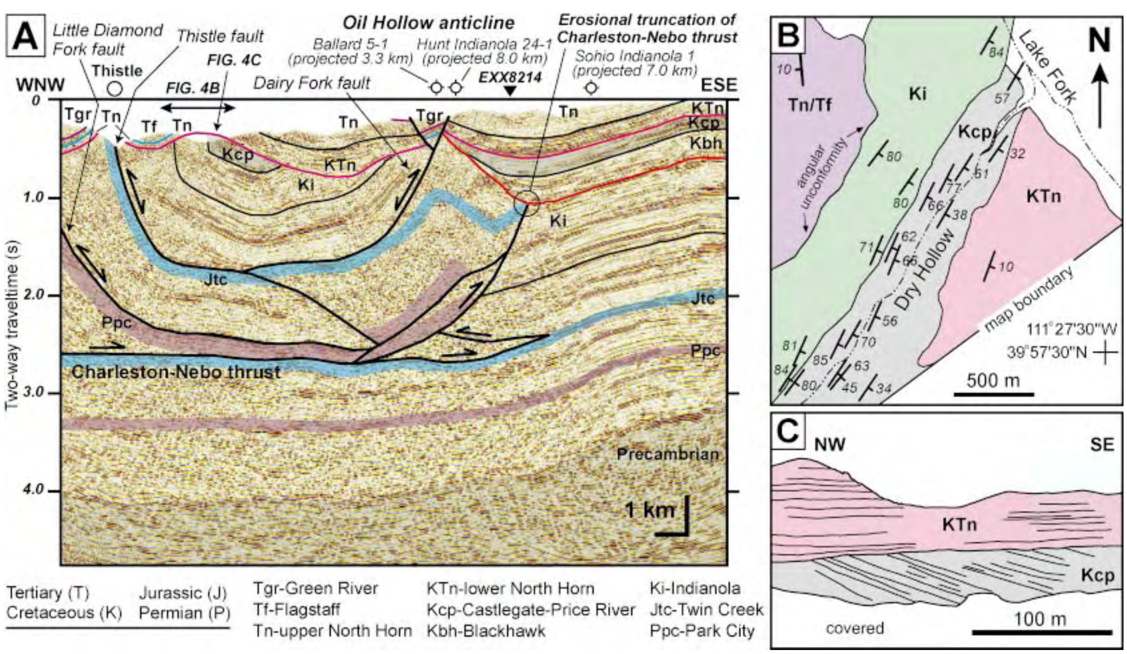

Figure 4. A: Interpreted seismic line EXX8212 depicting growth strata and crosscutting relationships (see text for discussion). Additional normal faults are shown. For approximate scale bar, vertical axis is based on velocity correction of 4.5 km/s. Penn.—Pennsylvanian; Cyn—Canyon. B: Simplified map of Dry Hollow area showing basal angular unconformity and upsection decrease in stratal dip within Castlegate–Price River succession. C: Sketch of field photograph depicting angular unconformity between Castlegate–Price River deposits and overlying basal North Horn Formation. Locations are shown in Figure 1.

1982). An abrupt upsection decrease from steeply to moderately east dipping orientations within the Castlegate–Price River interval is consistent with syndepositional tilting. At Red Narrows (section 5, Fig. 2), the subhorizontal North Horn lies in angular unconformity on moderately east dipping Castlegate–Price River strata (Fig. 4C), suggesting coeval deformation. In addition, a southward paleoflow component for the North Horn (Fig. 3C), rather than the ubiquitous east-southeastward flow, may signify drainage reorganization forced by growth of north-trending structures.

DISCUSSION

Evidence presented here is relevant for debates about coarse-grained progradational events in foreland basins and the relative roles of eustasy and tectonics. Our data indicate that $>$200 km of progradation of the Campanian clastic wedge at a rate exceeding $\sim$20 mm/yr was synchronous with shortening in the Charleston-Nebo salient. This rapid progradation event is comparable to rates of fluvial progradation in the Himalayan foreland (Burbank et al., 1988). Provenance data and improved correlations for proximal strata indicate an abrupt change in sediment composition coincident with the onset of internal shortening in the Charleston-Nebo salient and uplift of the Santaquin culmination. Widespread exposure of the Pennsylvanian–Permian Oquirrh Group within the roof sheet of the Santaquin duplex generated a pulse of quartz-dominated sediment to the basin in the form of the Castlegate Sandstone.

Although eustatic changes may have coincided with progradation, no causal link can be made between sea level and the observed provenance change (e.g., Miall and Arush, 2001; Lawton et al., 2003). Moreover, spatial proximity suggests that the Charleston-Nebo thrust system, rather than the commonly cited Canyon Range and Pavant thrusts, was not only a major contributor of sediment, but also a principal driver of flexural accommodation in the Book Cliffs.

Although tectonic processes in the Charleston-Nebo salient can account for sediment-dispersal patterns and loading in the Utah foreland, initial Laramide uplift of basement-involved intraforeland structures, such as the San Rafael swell and Uncompahgre uplift (Fig. 1), may have accentuated Castlegate progradation by reducing subsidence and accommodation rates (Lawton, 1983; Franczyk et al., 1990; Van Wagoner, 1995; Guiseppe and Heller, 1998; Miall and Arush, 2001). Castlegate subsidence rates may have been further reduced along the Utah-Colorado border, where ooidal ironstones overprinted by pedogenesis indicate slow accumulation (Van Wagoner, 1995), possibly related to a forebulge (Yoshida et al., 1996; Miall and Arush, 2001) or shoaling above a growing Uncompahgre uplift.

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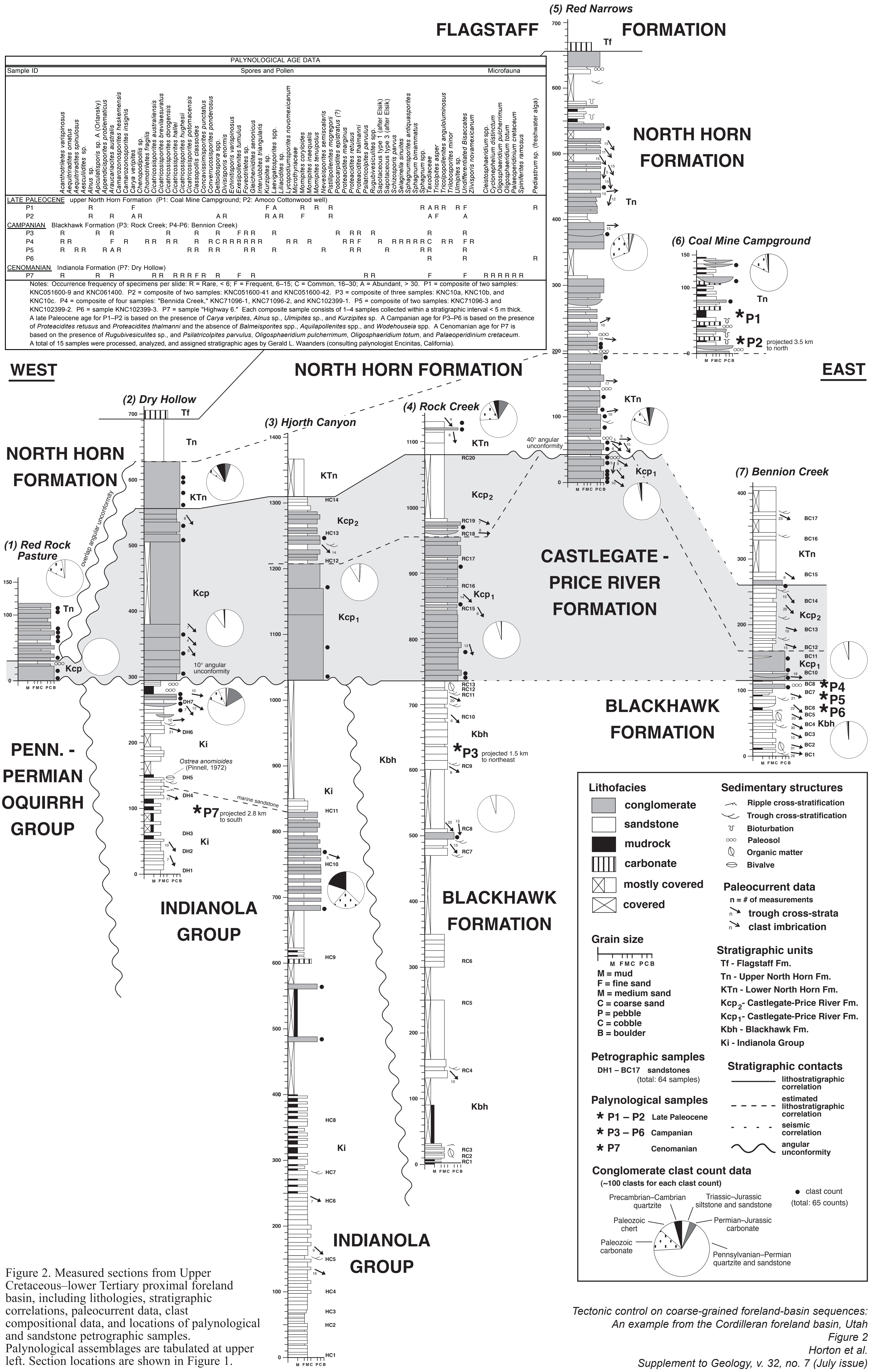

PALYNOLOGICAL AGE DATA

Sample ID	Spores and Pollen																																																										Microfauna						
	Acanthotriletes varispinosus	*Aequitriradites ornatus*	*Aequitriradites spinulosus*	*Aesculiidites* sp.	*Alnus* sp.	*Apiculatisporis* sp. A (Orlansky)	*Appendicisporites problematicus*	*Araucariacites australis*	*Camarozonosporites heskemensis*	*Camarozonosporites insignis*	*Carya veripites*	*Chenopodipollis* sp.	*Chomotriletes fragilis*	*Cicatricosisporites australiensis*	*Cicatricosisporites brevilaesuratus*	*Cicatricosisporites dorogensis*	*Cicatricosisporites hallei*	*Cicatricosisporites hughesii*	*Cicatricosisporites potomacensis*	*Classopollis classoides*	*Concavissimisporites punctatus*	*Converrucosisporites ponderosus*	*Deltoidospora* spp.	*Divisisporis enormis*	*Echinitisporis varispinosus*	*Exesipollenites tumulus*	*Foveotriletes* sp.	*Gleicheniidites senonicus*	*Interulobites triangularis*	*Kurzipites* sp.	*Laevigatosporites* spp.	*Liliacidites* sp.	*Lycopodiumsporites novomexicanum*	*Microthyriaceae*	*Momipites coryloides*	*Momipites inaequalis*	*Momipites tenuipolus*	*Nevesisporites semiscalaris*	*Pistillipollenites mcgregorii*	*Podocarpidites epistratus* (?)	*Proteacidites marginus*	*Proteacidites retusus*	*Proteacidites thalmanni*	*Psilatricolpites parvulus*	*Rugubivesiculites* spp.	Sapotaceous type 1 (after Elsik)	Sapotaceous type 3 (after Elsik)	*Schizosporis parvus*	*Selaginella sinuites*	*Sphagnumsporites antiquasporites*	*Sphagnum bimammatus*	*Sphagnum* spp.	*Taxodiaceae*	*Tricolpites asper*	*Tricolpopollenites anguloluminosus*	*Trilobosporites minor*	*Ulmipites* sp.	*Undifferentiated Bisaccates*	*Zlivisporis novamexicanum*	*Cleistosphaeridium* spp.	*Cyclonephelium distinctum*	*Oligosphaeridium pulcherrimum*	*Oligosphaeridium totum*	*Palaeoperidinium cretaceum*	*Spiniferites ramosus*	*Pediastrum* sp. (freshwater alga)
LATE PALEOCENE upper North Horn Formation (P1: Coal Mine Campground; P2: Amoco Cottonwood well)																																																																		
P1					R						F																			F	A				R		R		R													R	A	R	R		R	F								R
P2					R			R			A	R											A	R						R	A	R			F				R														A	F				A								
CAMPANIAN Blackhawk Formation (P3: Rock Creek; P4-P6: Bennion Creek)																																																																	
P3	R					R		R								R				R			R			F	R	R			R									R		R	R		R								R					R								
P4	R	R						F		R			R	R		R	R			R		R	C	R	R	R	R	R	R				R	R		R					R	R	F			R		R	R	R	R	R	C		R	R		F	R							
P5	R		R	R			R	A	R										R	R		R	R				R	R			R							R				R	R				R					R	R					R								
P6																																																					R					R								R
CENOMANIAN Indianola Formation (P7: Dry Hollow)																																																																	
P7	R					R		R						R	R		R	R	R	F	R		R			F		R																R	R								F					F		R	R	R	R	R	R	

Notes: Occurrence frequency of specimens per slide: R = Rare, < 6; F = Frequent, 6–15; C = Common, 16–30; A = Abundant, > 30. P1 = composite of two samples: KNC051600-9 and KNC061400. P2 = composite of two samples: KNC051600-41 and KNC051600-42. P3 = composite of three samples: KNC10a, KNC10b, and KNC10c. P4 = composite of four samples: "Bennida Creek," KNC71096-1, KNC71096-2, and KNC102399-1. P5 = composite of two samples: KNC71096-3 and KNC102399-2. P6 = sample KNC102399-3. P7 = sample "Highway 6." Each composite sample consists of 1–4 samples collected within a stratigraphic interval < 5 m thick.
A late Paleocene age for P1–P2 is based on the presence of *Carya veripites*, *Alnus* sp., *Ulmipites* sp., and *Kurzipites* sp. A Campanian age for P3–P6 is based on the presence of *Proteacidites retusus* and *Proteacidites thalmanni* and the absence of *Balmeisporites* spp., *Aquilapollenites* spp., and *Wodehouseia* spp. A Cenomanian age for P7 is based on the presence of *Rugubivesiculites* sp., and *Psilatricolpites parvulus*, *Oligosphaeridium pulcherrimum*, *Oligosphaeridium totum*, and *Palaeoperidinium cretaceum*.
A total of 15 samples were processed, analyzed, and assigned stratigraphic ages by Gerald L. Waanders (consulting palynologist Encinitas, California).

Figure 2. Measured sections from Upper Cretaceous–lower Tertiary proximal foreland basin, including lithologies, stratigraphic correlations, paleocurrent data, clast compositional data, and locations of palynological and sandstone petrographic samples. Palynological assemblages are tabulated at upper left. Section locations are shown in Figure 1.

Tectonic control on coarse-grained foreland-basin sequences: An example from the Cordilleran foreland basin, Utah
Figure 2
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