DR2016264 for Hagadorn, J.W., Whiteley, K.R., Lahey, B.L., Henderson, C.M., and Holm-Denoma, C.S., 2016, The Permian–Triassic transition in Colorado, in Keller, S.M., and Morgan, M.L., eds., Unfolding the Geology of the West: Geological Society of America Field Guide 44, doi:10.1130/2016.0044(03)

CORRELATION AND DEVELOPMENT OF NOMENCLATURE OF THE LYKINS FORMATION: FRONT RANGE

Age (left columns, top to bottom)		Jurassic; Early Triassic; Permian: Guadalupian and Ochoan(?), Leonardian, Wolfcampian; Pennsylvanian: Virgilian
Hayden (1869-1879)	Colorado Front Range	Jurassic; Trias or "Red Beds"
Marvine (1874)	South Platte to Little Thompson	Jurassic; Trias
Cross (1894)	Pikes Peak	Morrison Formation; Fountain Formation
Emmons, Cross & Eldridge (1896)	Denver Basin	Morrison Formation; Wyoming Formation: Upper Division; "creamy sandstone"; Lower Division
Fenneman (1905)	Boulder	Morrison Formation; Dr. Bond ss; Lykins Formation: "Crinkled Sandstone"; Lyons Sandstone; Fountain Sandstone
Butters (1913)	Morrison	Morrison Formation; Lykins Formation: "soft, red shales"; "Crinkled sandstone"; "soft red Lykin shales"; Lyons Sandstone; Fountain Formation
Condra, Reed & Scherer (1940, rev. 1950)	Owl Canyon, Northeastern Colorado	Morrison Formation; Sundance Formation; Jelm Formation; Phosphoria Group: Spearfish Formation (redefined); "Freezeout beds": limestone, gray-red, sandy; gypsum and shale interbeds; Forelle ls; Glendo sh; Minnekahta ls; Opeche sh: red shales and sandstone interbeds; gypsum and shale interbeds; Lyons Formation; Owl Canyon Formation; Ingleside Formation; Fountain Formation
LeRoy (1946)	Golden	Morrison Formation; Ralston Creek Formation; Lykins Formation: Strain sh; Glennon ls; Bergen sh; Falcon ls; Harriman sh; Lyons Formation; Fountain Formation
Burk & Thomas (1956)	Central Wyoming	Chugwater Formation; Goose Egg Formation: red shale, siltstone; Little Medicine member; red shale, siltstone; Ervay member; gypsum and red shale and siltstone; Forelle ls; Glendo sh; Minnekahta ls; Opeche sh; Casper Formation
Broin (1957)	Lykins Gulch	Morrison Formation; Entrada Sandstone; Lykins Formation: Upper Lykins: Red Hill sh; Park Creek ls; Stonewall and Livermore shales; Lower Lykins: Forelle ls; Glendo sh; Falcon tongue of the Minnekahta ls; Harriman sh; Lyons Sandstone; Fountain Formation
Pearson (1972)	Northeastern Colorado	Chugwater Formation; Red Peak fm; Goose Egg Formation: Upper Goose Egg; Forelle ls; Glendo sh; Minnekahta ls; Blaine gypsum; Lyons Sandstone; Satanka/Owl Canyon Formation; Ingleside Formation; Fountain Formation
Wiggs (1986)	Morrison	Morrison Formation; Lykins formation: Strain sh; Glennon ls; Bergen sh; Falcon ls; Harriman sh; Lyons Formation; Fountain Formation
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Hagadorn et al (2016)	Terminology used in this Field Guide	Ralston Creek Formation; Sundance/Entrada Formation; Jelm Formation; Lykins Formation: Strain sh: Red Hill sh; Park Creek ls; Stonewall Creek sh; Poudre ls; Livermore sh; Forelle ls; Glendo sh; Falcon ls; Harriman sh: Greenacre Lentil; Blaine gypsum; Basal Carbonates; Lyons Sandstone; Owl Canyon Formation; Ingleside Formation; Fountain Formation

Figure S1. Correlation and development of the nomenclature of the Lykins Fm. and associated Permian-Triassic strata of Colorado's Front Range (Fig. 1). The age assignments of the units are historical in nature, and do not reflect our current working hypothesis for the age of the various members of the Lykins Fm.. *The Greenacre Lentil, which overlies the Blaine Gypsum, and the basal carbonates that underlie it, are not formally named units of the succession. But they are used in this contribution, following their common informal use in the oil and gas industry.

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		Hill (1899)	Lee (1917)	Maher & Collins (1952)	Shaw (1956)	Maher & Collins (1952)		Shaw (1956)	Mudge (1967)		Maughan (1980)	Kauffman (1986)		Merewether (1987)
		Las Animas County Colorado	Raton Basin Colorado	Huerfano County Colorado (section #20)	Sangre de Cristo Mtns (section #1)	Baca County Colorado (section #12)		Southeastern Colorado (section #8)	Eastern Colorado Western Kansas		Eastern Colorado Western Kansas	Pinon Canyon Maneuver Site, Las Animas County, Colorado		Southeastern Colorado
		(Dakota: Cretaceous)	(Morrison: Cretaceous)		(Santa Rosa Fm: basal unit of Dockum, Upper Triassic)	(Dockum Group: Upper Triassic)		(Dockum Group: Upper Triassic)	(Dockum Group: Upper Triassic)			Entrada Formation: Jurassic However, based on research published by Heckert et al, 2012, this is currently thought to be the Red Draw member of the Jelm Fm: Middle Triassic		(Dockum Group: Upper Triassic)
PERMIAN	Guadalupian	Sangre de Cristo Fm	Undifferentiated "red beds" ranging in age from Pennsylvanian or older, to possibly Triassic; sitting on PreCambrian basement	Lykins Fm	unnamed unit			Taloga Fm		Taloga Fm	Taloga Fm	Lykins Formation	Strain sh	Taloga Fm
							Day Creek dolomite	Day Creek dolomite		Day Creek dolomite	Day Creek dolomite		Forelle ls	Day Creek dolomite
										Whitehorse Ss	Whitehorse Ss		shales and sandstones lower contact not exposed	Whitehorse Ss
	Leonardian			Lyons Fm		Nippewalla Group	Blaine Fm	Blaine Fm	Nippewalla Group	Dog Creek Sh	Dog Creek Sh			Nippewalla Group
										Blaine Fm	Blaine Fm			
					Glorieta Fm			Lyons Fm		undifferentiated units (Harper St, Salt Plain Fm, Cedar Hills Ss & Flowerpot Sh)	Nippewalla Group			
				Fountain Fm	Yeso Fm	Sumner Group	Stone Corral	Sumner Group		Stone Corral Fm	Stone Corral Fm			Sumner Group
										Ninnescah Sh	Ninnescah Sh			
										Wellington Fm	Wellington Fm			
	Wolfcampian				Sangre de Cristo Fm	Chase Group			Chase Group	Nolans Ls	Chase Group			Chase Group
										Odell Sh				
										Winfield Ls				
										Doyle Sh				
										Barneston Ls				
										Matfield Sh				
							Wreford Ls			Wreford Ls				
						Council Grove Group			Council Grove Group	Speiser Sh	Council Grove Group	?		Council Grove Group
										Funston Ls				
										Blue Rapids Sh				
										Crouse Ls				
										Easly Creek Sh				
										Bader Ls				
										Sterne Sh				
										Beattie Ls				
										Eksridge Sh				
							Grenola Ls			Grenola Ls				
										Roca Sh				
										Red Eagle Ls				
										Johnson Sh				
							Foraker Ls			Foraker Ls				
						Admire Group			Admire Group	Janesville Sh	Admire Group			Admire Group
										Falls City Ls				
										Onaga Sh				
PENNSYLVANIAN														

Figure S2. Correlation and development of the nomenclature of Permian-Triassic strata exposed in southeast Colorado, with emphasis on the Whitehorse Sandstone, Day Creek Dolomite, and Taloga Formation (Fig. 1).

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GSA DATA REPOSITORY ITEM S3: METHODS

Stratigraphy & Sedimentology

To assess the Permian-Triassic transition in Colorado in the Lykins Fm. and its equivalents, we conducted fieldwork at 32 localities and examined 21 partial or complete cores of the units. Only data from the Front Range and southeast Colorado surface exposures are presented here, because this contribution is an early progress report. Except where noted, all images as well as collected fossils, rock samples and thin-section billets are keyed to Figs. 1-2. Many of our study sites are on private land or sensitive public lands where permits are required for fieldwork; thus throughout the text we refer to locality numbers rather than to sites (e.g., referring to “section F4” rather than “Miriam Smith’s Ranch”). Detailed locality coordinates are available upon request. For the 16 Front Range and southeast Colorado reference sections, 420 standard thin sections were cut, stained and examined to petrographically characterize sedimentology, paleontology, depositional environments, and diagenesis of the Lykins Fm. and its equivalents.

Geochronology

A 5-10 kg sandstone sample from each target horizon (solid circles in section F13, Fig. 1) was processed using conventional mineral separation techniques including: crushing, grinding, sieving, Wilfley table density separation, magnetic separation, and heavy liquids separation. Concentrated zircon splits were poured onto double-sided tape and mounted in epoxy, ground and polished to half thickness to expose their internal structure, and imaged in transmitted and reflected light as well as SEM-based cathodoluminescence. Detrital zircons were ablated using a Photon Machines 193 nm Analyte Excite laser ablation system with spot sizes between 20 and

25 um at 5 Hz and ~5 mJ laser energy with an energy density of 6 J/cm^2. Ablated material was transported to a Nu Instruments AttoM high-resolution, double focusing, single-collector ICPMS. With the magnet set at a constant mass, the flat tops of the isotope peaks were measured at the following masses by rapidly deflecting the ion beam: ^{202}Hg, $^{204}(Hg+Pb)$, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{235}U, and ^{238}U with a 30 s on-peak background measured prior to each 30 s analysis. Raw data were reduced using Iolite™ (Paton et al., 2011) to subtract on-peak background signals, correct for U-Pb downhole fractionation, and normalize the instrumental mass bias using external, well-characterized, mineral standards. Ages are corrected by standard sample bracketing with the primary zircon standard Temora2 (417 Ma; Black et al., 2004) and secondary standards Plešovice (337 Ma; Slama et al., 2008), and an in-house standard WRP-63-08 (1707 Ma; Wayne Premo, personal commun., 2015) used at the USGS Central Mineral and Environmental Resources Science Center LA-ICPMS Isotope Lab. Reduced data was compiled into concordia and probability density plots using Isoplot 4.15 (Ludwig, 2012). Analyses with discordance greater than 15% were excluded from probability density plots. Analyses younger than 500 Ma were also visually inspected for degree of concordance. In general the $^{207}Pb/^{206}Pb$ ages become more precise for older zircons due to the relative abundance of ^{235}U (parent to ^{207}Pb daughter product) in the early Earth. $^{207}Pb/^{206}Pb$ ages are equally imprecise as $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages at about 1400 Ma, therefore, the preferred age for zircon greater than 1400 Ma is the $^{207}Pb/^{206}Pb$ age.

Paleontology

Only samples that were collected in-situ and logged into reference sections were considered for interpretation, with the exception of a vertebrate trackway, which was collected from float ~60 m above the Park Creek Member near section F13 (Figs. 1, 2). Thin-sections spanning all the representative lithologies in sections F1-F13 and S1-S2 were systematically examined for microfossils at 40x and 100x on a petrographic microscope. We did not search for nannofossils or palynomorphs, except in two rare grey-black calcareous shales from the Lykins Fm., where they mantle the Falcon Member at a locality near section F13. An ~15 kg bulk limestone or dolostone sample was processed for microfossils from each of the six Lykins Fm. carbonates at locality F12 as well as from each of the Falcon coquinas in sections F3 and F13. These carbonates were cleaned then dissolved in 10% buffered acetic acid for 3-4 days, with all particles greater than 75 µm retained by sieving. Residues were rinsed, dried and then separated in tetrabromoethane. The resulting heavy fraction was hand-picked under a binocular microscope. Identified microfossils mounted on slides and imaged via SEM.

Chemostratigraphy

Petrographic screening of all limestones, dolostones, and calcareous siliciclastics was conducted under polarized and cross-polarized light on a petrographic microscope, and where diagenetically least-altered phases (dominantly micrite, dolomicrite, or ooids) were identified, counterpart billets of those samples were microdrilled for analysis. Samples from sections F13-F12 were analyzed at the University of Arizona Environmental Isotope Laboratory where the $\delta^{18}O$ and $\delta^{13}C$ of least-altered carbonate phases was measured using an automated carbonate preparation device (KIEL-III) coupled to a gas-ratio mass spectrometer (Finnigan MAT 252). Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C. The isotope ratio measurement was calibrated based on repeated measurements of NBS-19 and NBS-18 and precision was ± 0.10 ‰ for $\delta^{18}O$ and ±0.08‰ for $\delta^{13}C$ (1 sigma).

The remaining samples were analyzed at the University of Utah SIRFER lab, where powders were weighed using a Sartorious microbalance, loaded into 4.5 ml flat-bottomed borosilicate vials (Labco) and capped with Labco butyl rubber septa. These were transferred to a Thermo Fisher Scientific system comprised of a GasBench II, PAL autosampler, ConFlow IV interface and a MAT 253 mass spectrometer. Vials were flushed for 6 mins on a PAL autosampler, with Ultra High Purity grade helium (99.999% He) at a flow rate of 50 mL/min. During flushing the vials were kept in a 50° C aluminum block. Samples were reacted with 10 droplets of 104% phosphoric acid (H_3PO_4) (kept at 50° C) to CO_2 gas. Samples were allowed to equilibrate for 12 hours before analysis. During analysis using the PAL autosampler the produced CO_2 gas in the vials was collected using a sampling loop of 100 µL and transported to the mass spectrometer. Nine individual gas injections per analysis were made for each sample and for the reference materials; their average was taken as the final number. Three sets of reference materials were used to calibrate the system and unknown samples, including Carrara marble, LSVEC and Marble-Std. Carrara and LSVEC was used as primary reference materials and Marble -Std used as secondary reference material to cross check the final number. The oxygen fraction factor was calculated using the alpha value proposed by Swart et al. (1991). The average analytical uncertainty for analyzed samples was <0.08 for $\delta^{13}C$ and <0.10 for $\delta^{18}O$; samples yielding low CO_2 output were excluded from reported results.

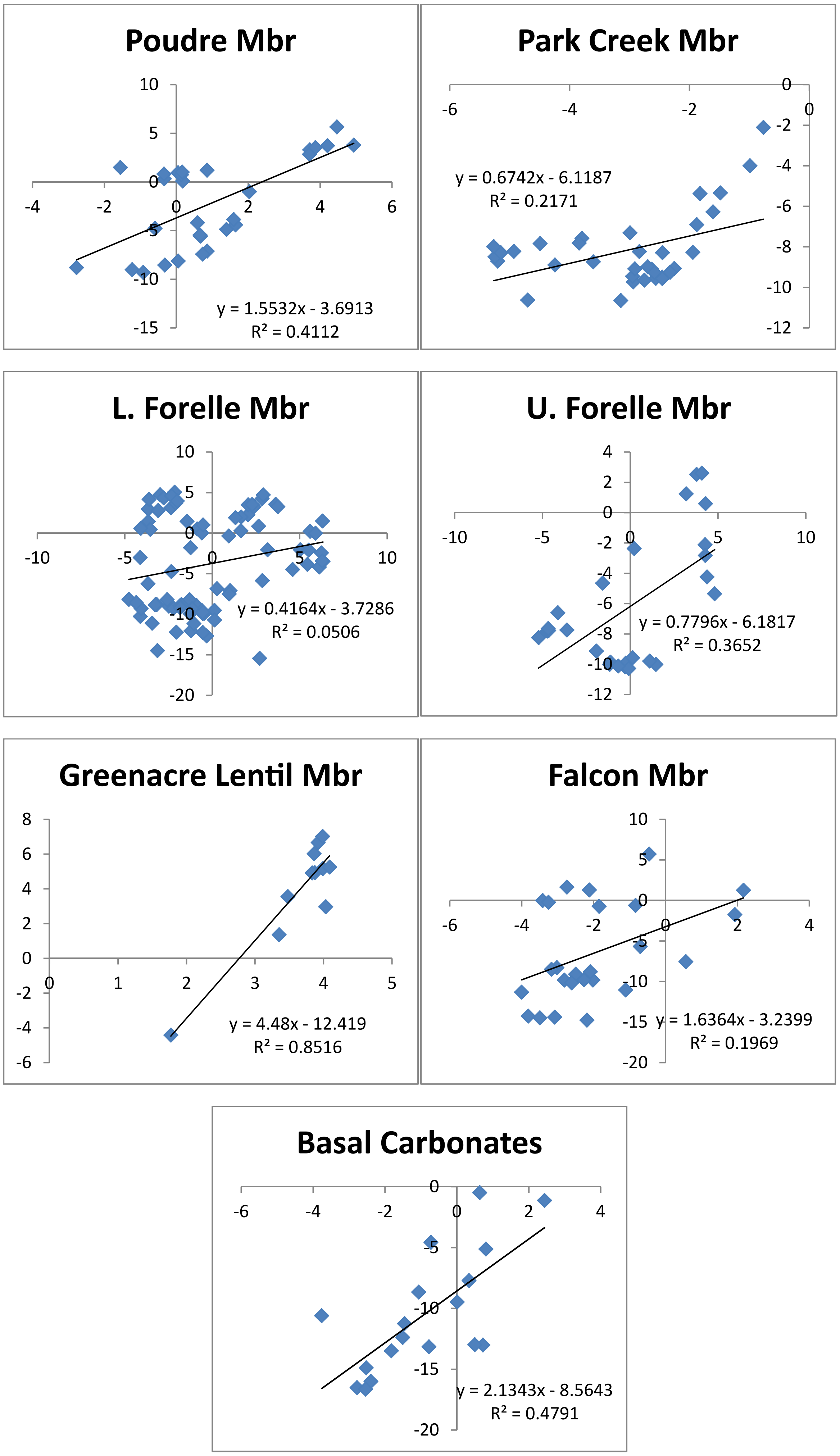

Figure S4. Cross-plots of ^{13}C (horizontal axis) vs. ^{18}O (vertical axis) for each of the carbonate-dominated intervals of the Lykins Formation. The three thin basal carbonates are plotted together whereas the Lower and Upper Forelle Member are separated. Results are preliminary.