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Final Report for two-year OSMP-BCPOS-JCOS proposal: "*Identifying a mass extinction in Front Range open space: Age & environments of the Lykins Formation*"

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Project Summary:

For this project, we analyzed the paleontology, sedimentology, diagenesis, geochemistry and geochronology of the Lykins Formation in JCOS, OSMP, and BCPOS, integrating results from this work with data from other regional exposures of the Lykins Formation and equivalent units. Key outcomes include: A) identification of the overall age of the Lykins Formation and the interval in which the Permian-Triassic boundary occurs; B) assessment of the environments that produced the Lykins and associated strata; and C) characterization of locations in Open Space parcels that may be suitable for connecting the public to the science and history of these rocks. These accomplishments and opportunities are synthesized below.

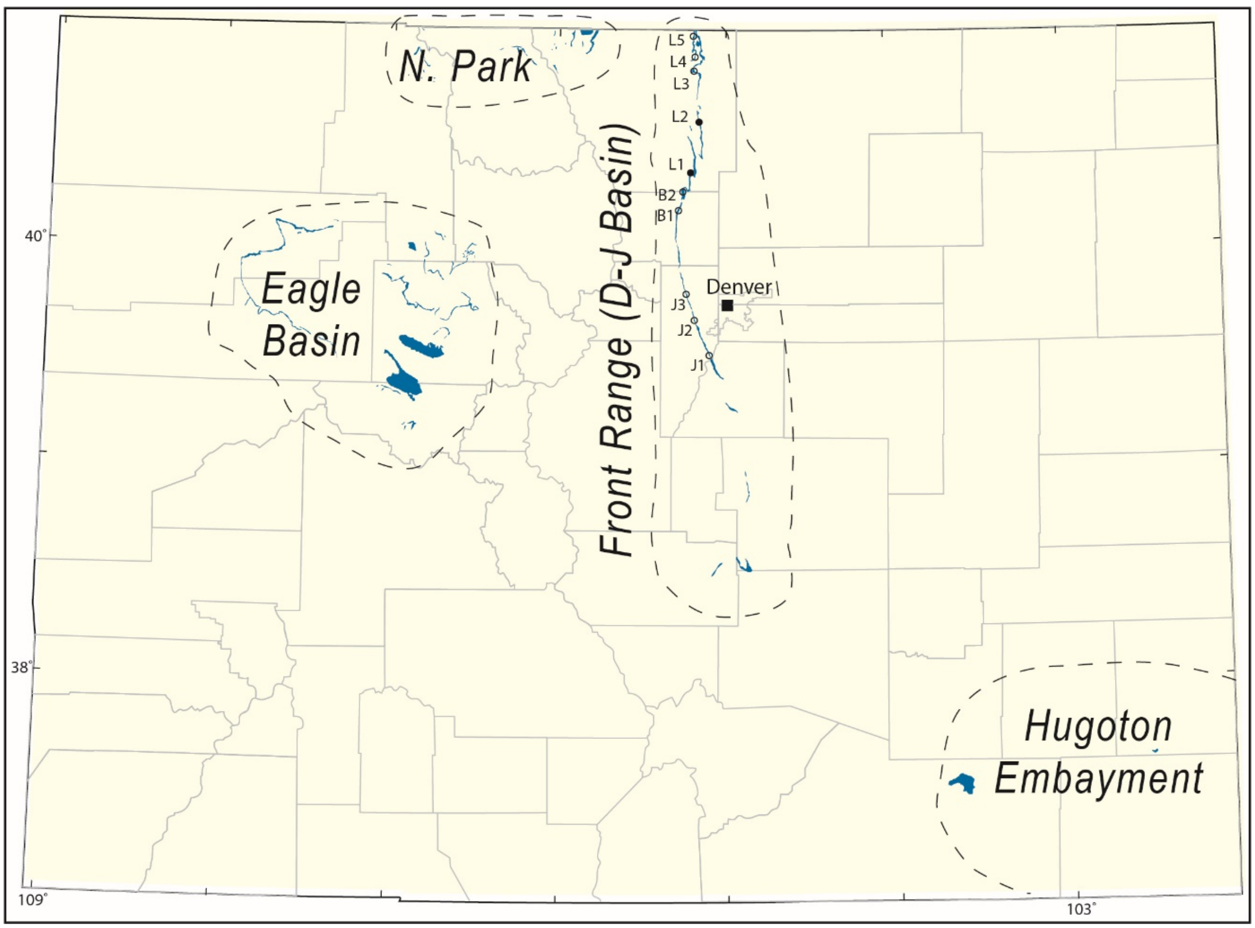

Figure 1: *Major basins (dashed outlines) in which Permian-Triassic sedimentary rocks (blue) are exposed.*

A) Age of the Lykins Formation and position of the Permian-Triassic transition

The studied outcrops represent surface exposures of strata that also occur below the surface in the Denver-Julesberg Basin, and they have correlatives in three other Colorado basins, known as the Eagle Basin, Hugoton Embayment, and North Park Basin (Fig. 1). Although the focus of this scholarship is on the surface exposures in OSMP-BCPOS-JCOS, (J1-J3, B1-B2 in Figs. 1, 3) we augment them with data from core (DH01-640; L1-L2 in Fig 1) and outcrop in Larimer County Open Space (L3-L5 in Figs. 1, 3) and elsewhere in Colorado.

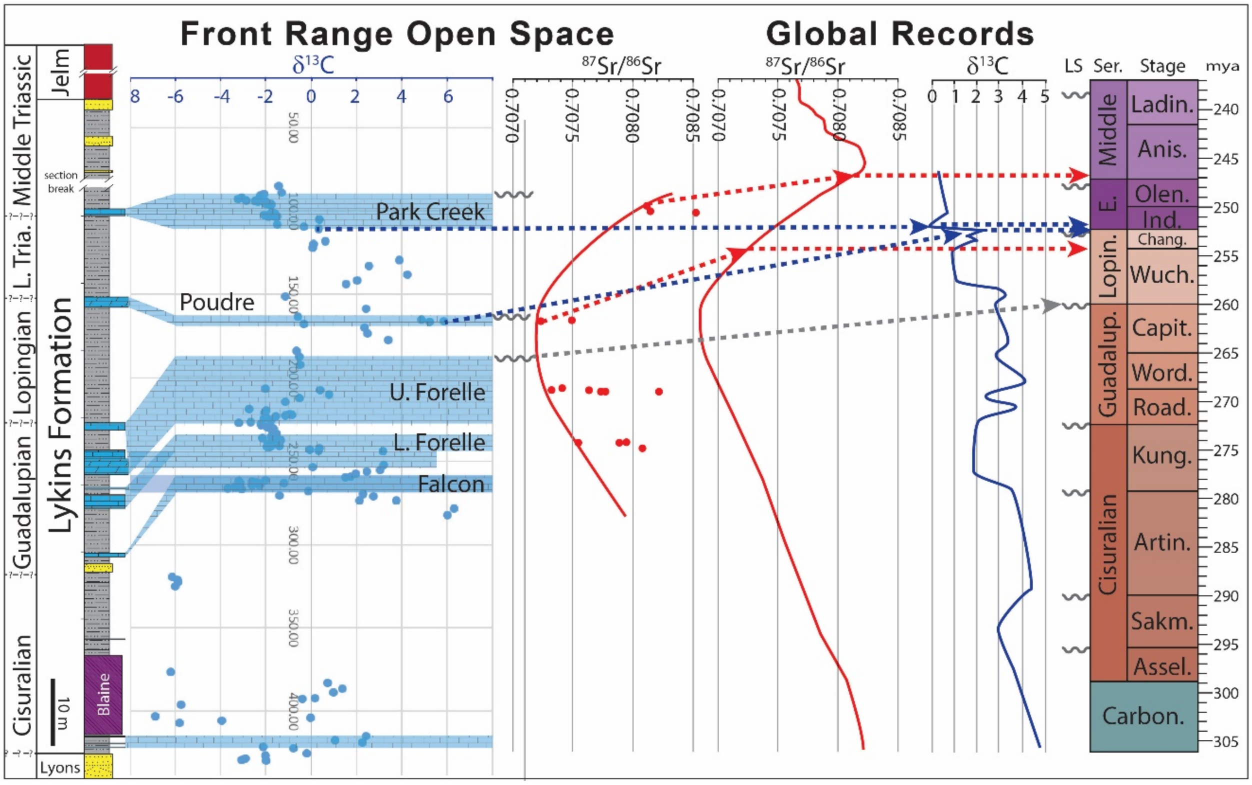

Figure 2: *Geochronologic framework for the Lykins Formation in Colorado's Front Range Open Spaces, grounded in chemostratigraphic data from core DH01-640 at left. Global chemostratigraphy and geochronology, together with Permian (brown) and Triassic (purple) time periods and stages at right. The data illustrate that the Permian-Triassic transition is probably at or very close to the Poudre Limestone Member of the Lykins Formation.*

Based on analysis of these exposures and core, the Lykins Formation spans the latest Permian and earliest to middle Triassic periods, with the transition between the two epochs falling close to the Poudre Limestone Member of the Lykins Formation (Fig. 2). In part this age span is based on Roadian age conodont microfossils found in the Falcon Member of the Lykins Formation elsewhere in Colorado, and Middle Triassic detrital zircons found in the overlying Jelm Formation (Fig. 5). Throughout Colorado and in the studied Front Range Open Spaces, the Forelle contains a regionally extensive karsted surface that is dominated by solution collapse features. This suite of features signals the presence of a substantial unconformity (=gap in time and associated erosional event), which we interpret to represent the global low in sea-level that is known from the end of the Guadalupian stage of the Permian period (grey dashed line in Fig. 2). The overlying Poudre Limestone contains a nearly +5‰ δ^{13}C excursion that mirrors a similar globally synchronous excursion known from the boundary between the latest Permian stage (Lopingian) and the Early Triassic period (lower blue dashed line in Fig. 2). Similarly, the leastradiogenic $^{87}Sr/^{86}Sr$ signature in the entire Lykins Formation occurs in the Poudre Limestone, and matches the values known for the Permian-Triassic transition elsewhere (lower red dashed line in Fig. 2). $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ values for the overlying Park Creek Limestone are also internally consistent with global patterns, and suggest deposition during earliest Triassic time.

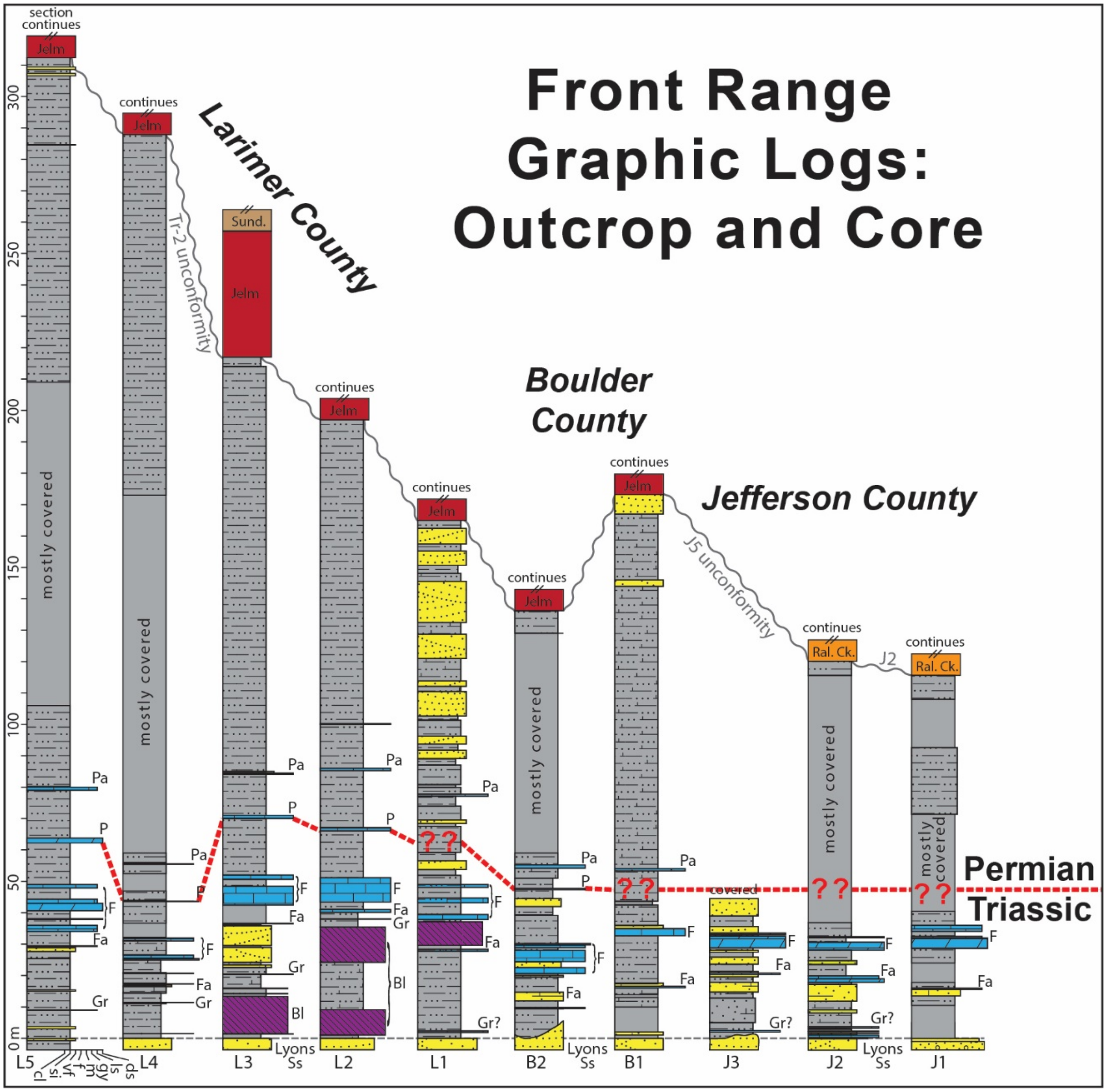

Figure 3: *Representative measured sections of strata exposed in Front Range Open Spaces, illustrating the hypothesized position of the Permian-Triassic transition (red dashed line) and progressively more erosive removal of the tops of these successions from north to south (grey wiggly lines). Key: Yellow (sandstone), grey (siltstone), blue (limestone-dolostone), purple (gypsum-anhydrite), red/brown/orange (overlying units of rock).*

Although the Permian-Triassic transition ought to fall in or very near the Poudre Limestone Member of the Lykins Formation, unfortunately this unit is thin, often covered, and difficult to identify where outcrops are overgrown or have extensive soil development (red question marks in Fig. 3). Moreover, in some areas, the upper portions of the Lykins Formation have been eroded by geologically younger events associated with subsequent mountain-building or flooding by inland seas (Fig. 3). Thus, although the Lykins Formation is present at all studied Open Spaces, we were not always able to identify the Poudre because it may not be everywhere present or preserved.

B) Environments

Everywhere the Lykins Formation interfingers with the cross-bedded fine to very fine well-sorted tan-to-pink sandstones of the Lyons Formation, a unit that represents deposition in and between giant eolian (wind-dominated) dunes (Fig. 4). The unit contains classic wind-blown bedforms and sand grain populations, like those of the dune deposits represented by coeval formations elsewhere in Colorado (e.g., the Weber, Fryingpan, and Whitehorse Sandstones, Fig. 5).

Figure 4: *Oblique view of an ephemeral stream dissecting dunes like those that are thought to have produced the Lyons Sandstone. Image courtesy of IGP & DMNS.*

Thinly bedded red siltstone is the signature rock type of the Lykins Formation and although rare low-amplitude oscillation and ladder-shaped ripples and halite crystal impressions occur, the majority of siltstone and interbedded very fine sandstone is structureless. Windblown zircon crystal grains in these red siltstones are small, abraded, and are similar in age as those found in nearly every other Permian and Triassic rock in Colorado (Fig. 5). The Lykins has a remarkable absence of coarse sands, gravels, conglomerates, channels, or other structures typical of high velocity flow regimes common to rivers, streams, and landslides, and their absence also signals a near-absence of nearby topographic relief. Together these features suggest that the majority of the Lykins Formation accumulated as windblown dust became trapped on a broad, flat, wet landscape – an interpretation that is consistent with what we know of the regional paleogeography of this time period, where Colorado was situated near the middle of a vast supercontinent called Pangea, during a time when Pangea straddled the equator.

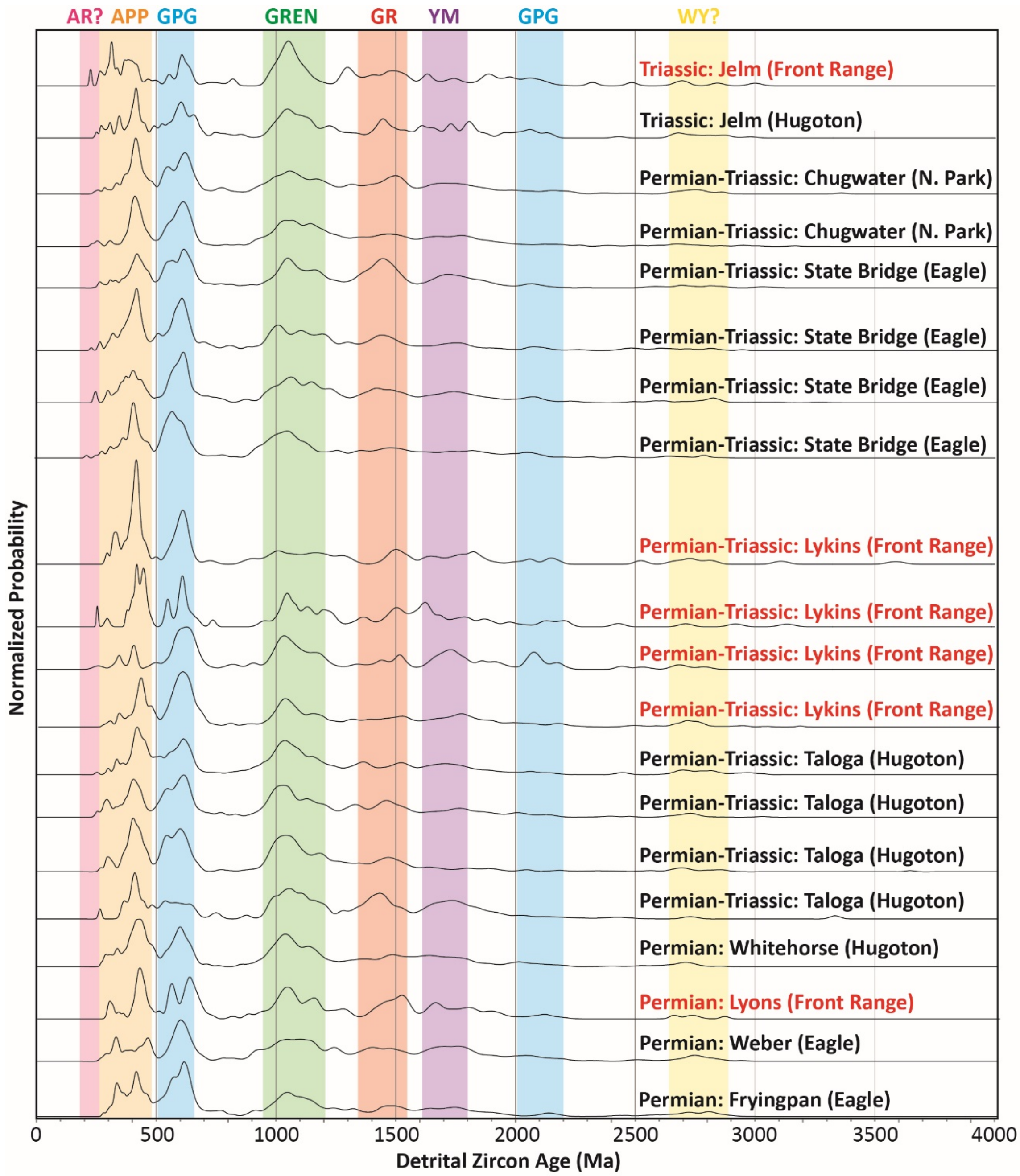

Figure 5: *Relative composition (normalized to 100%) of detrital zircon crystal ages of Front Range Open Space strata (red), compared to similar strata from Colorado's other sedimentary basins. The vertical color-shaded columns represent the different ancient mountain ranges from which these zircon crystals came, and gives a sense of the diversity of grains deposited locally.*

Intercalated in between the redbeds of the Lykins are a series of thin limestone and dolostone beds that reflect the flooding of this supercontinent by shallow seas, and the growth of beachball- to bus-sized microbial 'reefs' called stromatolites. These limestones record chemical changes through the Lykins that mirror global-scale perturbations in ocean chemistry that have been documented elsewhere in the world, and that are associated with mass extinction and oceanic overturn events. These limstones also bear microfossils characteristic of marine settings, such as ostracods, forams, sponge spicules, and calcispheres, as well as rare gastropods and bivalves. These strata, particularly the Forelle Limestone, are often eroded at their tops, and have features like terra rosa, karst, solution collapse breccias, and related geochemical signatures consistent with exposure of these limestones to rainwater after the interior sea retreated. Such features form today in stranded reefs and limestones in Florida, Belize and the Bahamas. The basal Lykins Formation also has a thick but easily eroded gypsum bed present, called the Blaine Gypsum, that is rarely exposed at the surface. It signals the evaporation of a distal tongue of an interior seaway, and deposition of this salt may have occurred in settings analogous to those of the Dead Sea or Persian Gulf.

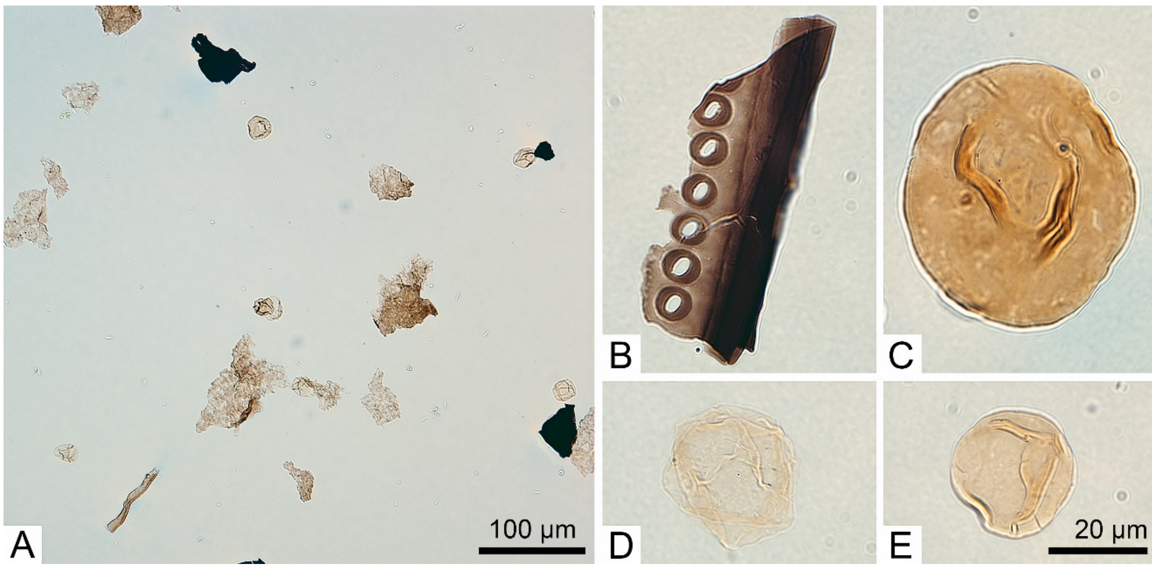

Figure 6: *Transmitted light micrographs of organic fossils from the basal black shale in the Lykins Formation, including A) miscellaneous debris; B) woody cuticle; C-E) marine acritarchs.*

Palynomaceral	3:CO-RMOS-6b	1:CO-MU-1AB	2:CO-MU-1C	4:DH01-640-L	5:DH01-640-R	7:DH01-640-FFF	6:DH01-640-QQ
I: Palynomorphs							
All	**135** (27.0%)	**0** (0.0%)	**0** (0.0%)	**0** (0.0%)	**0** (0.0%)	**1** (0.2%)	**0** (0.0%)
II: SOM							
Black wood	**72** (14.4%)	**0** (0.0%)	**119** (23.8%)	**16** (3.2%)	**0** (0.0%)	**8** (1.6%)	**18** (3.6%)
Brown wood	**37** (7.4%)	**4** (0.8%)	**21** (4.2%)	**2** (0.4%)	**1** (0.2%)	**0** (0.0%)	**0** (0.0%)
Charcoal	**0** (0.0%)	**3** (0.6%)	**0** (0.0%)	**0** (0.0%)	**0** (0.0%)	**0** (0.0%)	**0** (0.0%)
Cuticles	**227** (45.4%)	**0** (0.0%)	**0** (0.0%)	**0** (0.0%)	**3** (0.6%)	**0** (0.0%)	**0** (0.0%)
Phytoclasts	**23** (4.6%)	**0** (0.0%)	**82** (16.4%)	**104** (20.8%)	**122** (24.4%)	**221** (44.2%)	**295** (59.0%)
III: USTOM							
Amorphous	**6** (1.2%)	**493** (98.6%)	**278** (55.6%)	**378** (75.6%)	**374** (74.8%)	**270** (54.0%)	**187** (37.4%)
Total:	500	500	500	500	500	500	500

Figure 7: *Absolute and relative abundance of palynomorphs from Front Range Open Spaces.*

Additionally, plant-related microfossils known as palynomorphs occur in a rare black shale that immediately underlies the Blaine Gypsum, and includes pieces of woody debris and single-celled marine organisms called acritarchs (Fig. 6). Pairing data from this black shale with palynomorphs from core DH01-640 and the Blaine Gypsum allows an additional, independent assessment of depositional environments of the Gypsum-shale portion of the succession (Fig. 7).

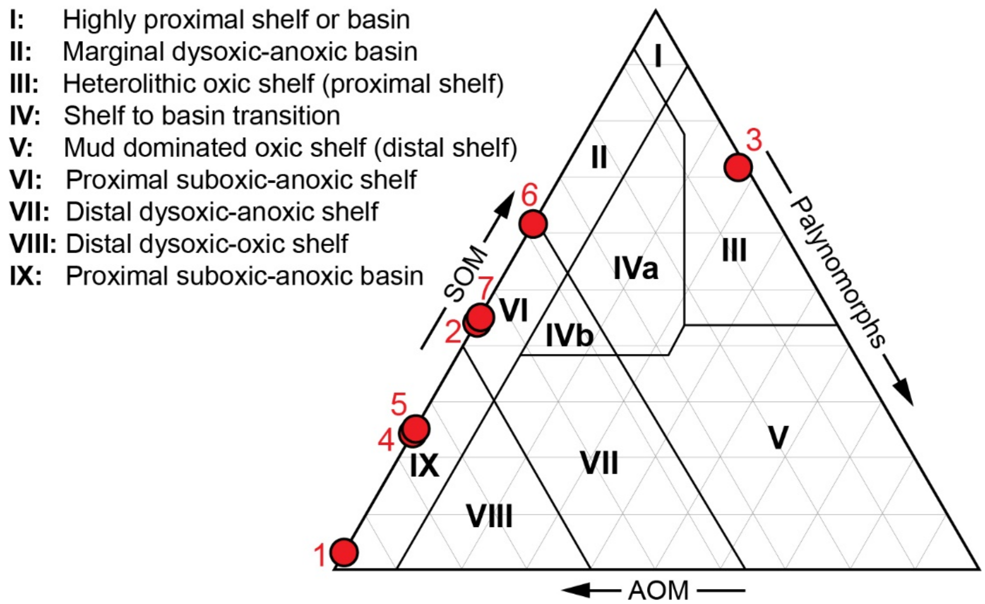

Figure 8: *Depositional environmental interpretation of palynomorphs from Front Range Open Spaces (red dots keyed to Fig. 6).*

Collectively, the data suggests deposition of these strata in a shallow near-shore basin that had low oxygen concentrations in its bottom waters, but that was periodically flushed by well oxygenated waters (Fig. 8). Such conditions are common in shallow epi-continental seas throughout earth history, such as Colorado's many Cretaceous interior seaways. Such a setting might have looked like the paleoenvironmental reconstruction in Figure 9.

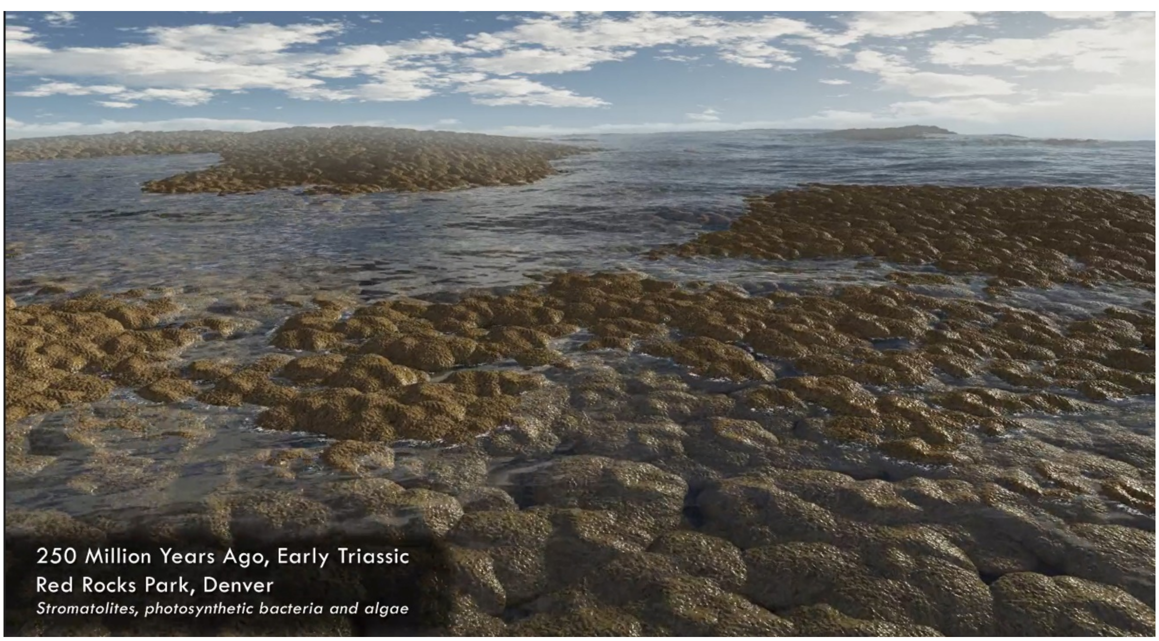

Figure 9: *Oblique view of an emergent stromatolite-covered seascape like that thought to have produced the Forelle Limestone. Image courtesy of IGP & DMNS.*

C) Opportunities & next steps

We see two major opportunities stemming from our collaboration with BCPOS, OSMP, and JCOS to study the Lykins Formation in Front Range Open Spaces.

First, there are fantastic opportunities to connect the public with the story of these rocks, to reveal the colorful geology and paleontology underfoot, and to partner with land stewards to integrate 'reading of these rocks' with outdoor experiences. Many of these opportunities are on or adjacent to existing trailheads and vistas and can be accomplished in an accessible manner. With this in mind we re-mapped exposures of key members of the Lykins Formation as part of our work, and have detailed these opportunities in the attached Appendix. This appendix keys open space resources with potential Lykins Formation interpretive opportunities, overlain on paired geologic, topographic, and trail maps. In the same vein, our DMNS team has begun partnering with Paul Weimer's Interactive Geology Project (IGP), as well as other scientific illustrators and animators to develop visually compelling content that can foster such experiences (e.g., Figs. 4, 9) and are excited to extend such work in new directions to benefit communities that visit our open spaces.

Second, based on this first two-year study, we have learned where the "target zone" in which the Permian-Triassic transition occurs, and emerging analytical techniques offer an opportunity to precisely identify the boundary with further work. For example, we now know to focus efforts on the Poudre Limestone and adjacent redbeds, and in this interval we can employ two techniques that were recently successfully used to identify the Permian-Triassic boundary in redbed successions in South Africa and North Texas. By using high-resolution magnetostratigraphy in tandem with two-phase-leaching and isotopic analysis of dolomite siltstone cements, geologists in Texas and South Africa were able to drive a proverbial "golden spike" into the boundary in these areas, and have inspired us to try to do the same here in Colorado.

We are grateful for your support over the last two years, and are eager to partner with you again to realize these further outreach and scientific opportunities, or to support others on your team to leverage these strata and their stories to public benefit.