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Physical Evidence for the Sequence Stratigraphic Model's Maximum Regressive Surface; Casper Formation, Southeastern Wyoming, United States of America

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Abstract

The original sequence stratigraphic model was developed in the 1980's to predict lateral and vertical relationships among rocks derived from siliciclastic depositional paleoenvironments. This model was based upon a juxtaposed onshore terrestrial coastal plain, beach and offshore passive margin siliciclastic basin. The Pennsylvanian/Permian Casper Formation in southeastern Wyoming contains strata developed from an onshore dune field adjacent to an offshore carbonate ramp, a combination of paleoenvironments rarely if ever previously examined in any sequence stratigraphic studies.

In the original siliciclastic model, systems tracts were established and unique physical signatures for individual tracts were defined. For example, the time of maximum transgression, when the relative sea level was turning around from its basin-most projection to a return toward the terrestrial, is evidenced by the maximum flooding surface (MFS), a thin, organic-rich condensed section. Analogously, there should also be physical evidence to demonstrate when the relative sea level has reached the time of maximum regression, when the relative sea level has reached its landward-most limit. Unfortunately, due to the characteristics and constraints of the depositional environments in the original model, there is no physical signature of when this limit is reached. In the Casper Formation, however, evidence has been found which suggests that there is a physical signature that indicates the time of maximum regression, a sequence of terrestrial sandstone units that exhibit a progression up-section from low-angle to high-angle and back to low-angle cross-bedding. This type of change in cross-bedding has been related to how much moisture was associated with the dunes, a proxy for how close or far the sands were being deposited from the shoreline.

Keywords: Maximum regressive surface, MRS, Sequence stratigraphy, Casper Formation, Carbonate platform, onshore dune field

Introduction:

Sequence stratigraphic models have been used for decades to predict the lateral and vertical changes in a stratigraphic succession, primarily as a tool for petroleum exploration. The initial model was created from analyses of strata formed along siliciclastic shorelines adjacent to oceanic basins [1, 2]. Accommodation and sediment influx are vital components in the model, and periodic changes in depositional style are commonly linked to fluctuations in relative sea level. These cycles operate on several scales, from first order changes that endure for hundreds of millions of years to fourth and fifth order cycles that last for tens of thousands of years. The mechanisms invoked to drive the changes in depositional style range from continental reorganization and opening of oceanic basins for the lower frequency periods to eustasy for the higher frequency ones. The eustatic changes in relative sea level in the latter case are commonly attributed to glacial fluctuations. The siliciclastic sequence stratigraphic model is composed of several genetic sequences that are separated by bounding discontinuities, predominantly defined by unconformities. The main stratal sequences that are developed range from a highstand, during which sediment deposition within the basin is essentially zero, to a lowstand, when sediment influx is at its greatest rate.

The publication of the siliciclastic sequence stratigraphic model precipitated numerous other studies, which sought to extend the concepts developed to a variety of other depositional paleoenvironments. Stratal successions that are primarily aeolian have had these stratigraphic principles applied to them [3-6] as well as systems that are dominantly carbonate platforms [7-11]. Studies of the latter type revealed that there are several additional variables to consider when modeling the carbonate paleoenvironment, such as the type of platform geometry that is developed, the number and kind of

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biota that comprise its community, and the water temperature. All of these interact to produce different models depending on the level of influence of these components.

Mixed siliciclastic-carbonate paleoenvironments have also been studied, ranging from aeolian dune/carbonate reef systems [12, 13] to clastic/evaporite lagoon/carbonate platform systems [14]. None of the iterations to mixed siliciclastic-carbonate sequence stratigraphic models addressed a juxtaposed aeolian dune field and carbonate mud platform. Therefore, the mixed siliciclastic/carbonate system that existed when the sediments that compose the Casper Formation strata were deposited is an example of a system that has not yet been previously analyzed in the context of sequence stratigraphic principles. While no petroleum reserves exist in the Casper Formation, other basins developed under similar depositional environments may have potential for hydrocarbon production. Figure 1 is a location map of the study area. Stratal sediments of the Pennsylvanian/Permian Casper Formation in southeastern Wyoming were deposited in and adjacent to an epeiric sea, with an aeolian dune field onshore and a simple, low angle carbonate ramp offshore [15, 16]. The study by Burns [15] focused on determining the sequence stratigraphic characteristics unique to this system in order to develop a predictive model for other sequences developed along similar coastlines. The Casper Formation contains several cyclic packages composed of transgressive and regressive units in the form of limestones and sandstones/siltstones respectively.

Regional Tectonic Setting

During Mississippian time, the North American craton experienced low-amplitude deformation, producing east-west-trending troughs in the Williston and Uinta basins and uplifts along the Montana arch and the Oquirrh-Uinta axis [17]. These areas of weakness were reactivated in Early Pennsylvanian time, resulting in extensive mid-continent uplifts that were cored by Precambrian basement rocks collectively known as the Ancestral Rocky Mountains [18, 19]. This produced a paleogeography (Figure 2) with a series

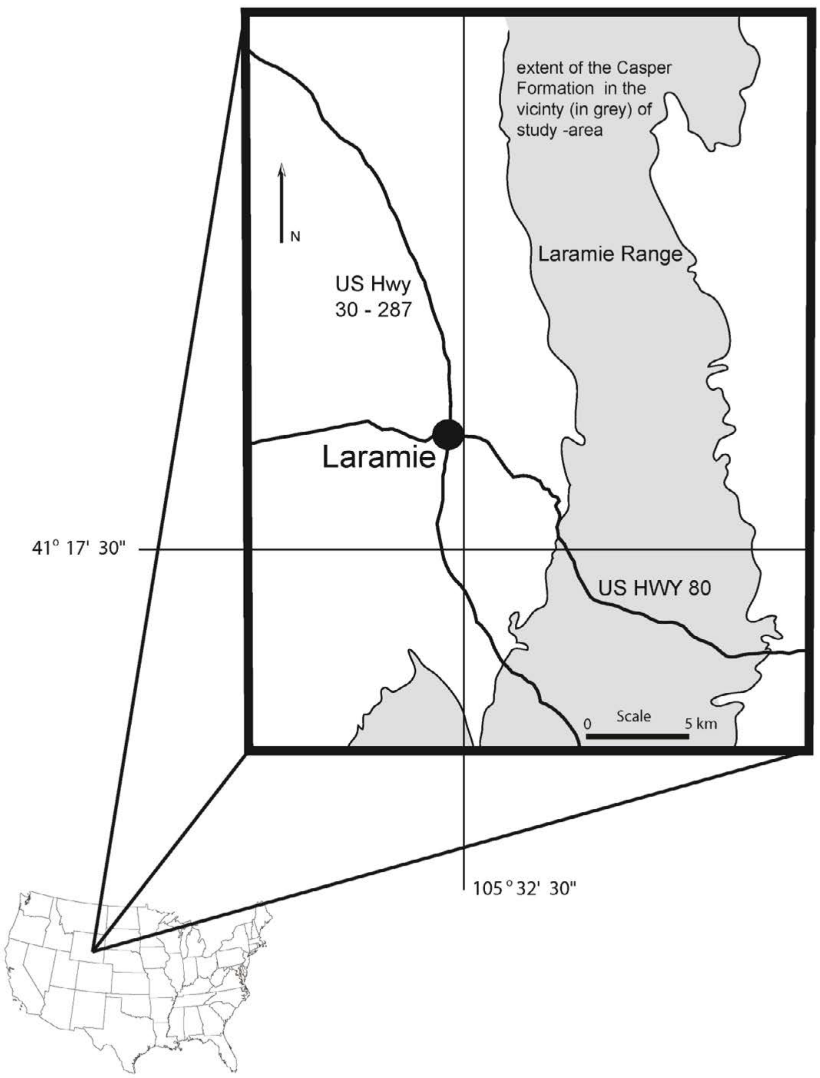

Figure 1: Location map; light grey region depicts the extent of the Casper Formation in the study area.

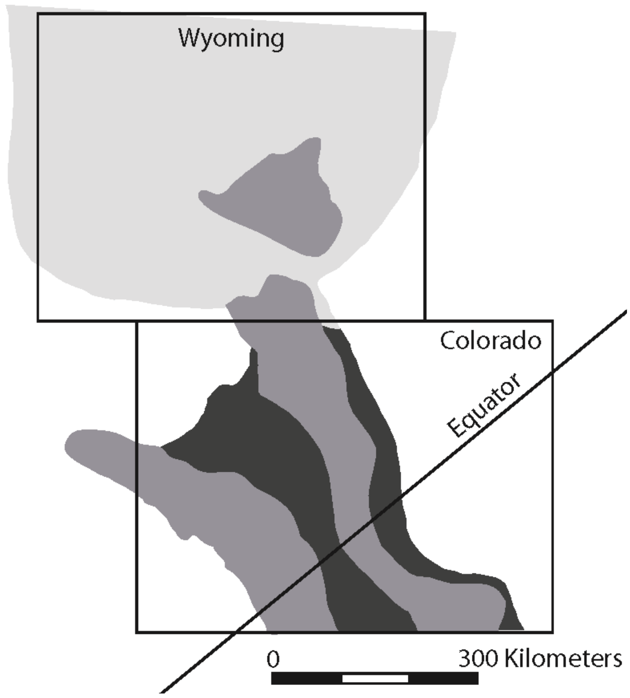

Figure 2: Paleoposition of the region during time of deposition of Casper Formation strata. Light grey area was an onshore dune field, medium grey areas represent topographic highlands and dark grey areas were adjacent depositional basins; modified from [20].

of discrete depocenters separated by intracratonic block uplifts [21]. The basins and uplifts began to emerge just before the beginning of Pennsylvanian time, although the signatures were subdued [22-26]. Uplifts active at this time included the Front Range, the Pathfinder and the Uncompahgre [27]. Estimates of relief exhibited by these uplifts range up to 6,000 meters (m) [28]. The exact nature of the faulting that produced these uplifts is a matter of debate, with researchers proposing both movement along high-angle faults with some strike-slip component [29] and steep reverse faults [21, 30]. Deformation increased throughout Pennsylvanian time, reaching its maximum tectonic expression during Middle Pennsylvanian. As the rate of deformation increased, so did the regional extent. Intracontinental basins and broad, uplifted blocks developed from southeastern Oklahoma (Arkoma Basin) to northeastern Nevada [19]. Tectonism continued until the end of Early Permian during which time the Front Range, Uncompahgre and Pathfinder uplifts continued to shed sediment into their adjoining basins [22, 31]. As a result of this sedimentation, the Wyoming shelf expanded until it became continuous with the Alberta shelf. The Ancestral Rockies to the west were emergent, shedding material to the east toward a shoreline hosting an aeolian dune field [32]. At least some of the siliciclastic material comprising the Casper Formation sandstone was derived from the Precambrian core and previously deposited sedimentary rocks that made up the Ancestral Rocky Mountains [33, 34]. Subsequent investigation suggests that there may also be some sediment influx into the basin from the northeast, perhaps from the Transcontinental Arch [35].

Concurrent with the tectonism, the Late Paleozoic was a time of southern hemisphere Gondwanaland glaciation, giving rise to global icehouse conditions [36] that lasted approximately 90 million years, and which also gave rise to a variety of tectonic/eustatic sedimentary sequences throughout the western United States. The beginning and end of the glacial age is attributed to large scale adjustments in continents and seas and their effect on global air-ocean circulation patterns [37, 38] as well as orbital forcing [39, 40].

The Casper Formation consists of a series of interbedded, small to large scale cross-bedded sandstone and limestone units gently dipping from 4 degrees to 11 degrees off of the topographic high of the Laramie Range into the Laramie basin [33, 41]. The formation varies in thickness from 243 m along the Laramie Range east of Laramie, Wyoming to less than 7.5 m near Sand Creek Pass southwest of Laramie [33]. In the study area for the overall sequence stratigraphic analysis, the unit averages 177 m. The limestone units commonly outcrop as prominent, ledge-forming features while the siliciclastic units are usually slope-covered and less readily exposed.

The Casper Formation overlies the PreCambrian Sherman Granite throughout most of its regional extent. In the northernmost portion in the Laramie Range, the Casper Formation overlies the Mississippian Madison Limestone [32]. The Casper Formation intertongues with and overlies the Pennsylvanian Fountain Formation, a primarily medial to distal fan deposit [42] that presumably fed siliciclastics to the dune fields and offshore depositional paleoenvironments of the Casper Formation. Normal marine salinity during the time of deposition is indicated by a diversity of stenohaline organisms including brachiopods, echinoderms and fusulinids [34]. Fusulinids indicate deposition of the sediments which later became the Casper Formation began in the southern part of the Laramie Range, with the northern part of the basin remaining emergent until Late Pennsylvanian [32]. The Casper Formation is overlain by the Permian Santanka Shale, which is interpreted either as a marine deposit [34, 43] or a continental floodplain deposit [44].

Physical Evidence in Sequence Tracts

In the Exxonian model [1], care was taken to not only explore the theoretical construct of how the individual tracts were developed but also to proffer the physical characteristics that stand out as distinctive markers of each particular. For example, the onshore migration of the relative sea level during the beginning of the Transgressive Systems Tract (TST) is preserved in the form of a ravinement surface – as the waters migrated landward, the energy from the waves cannibalized the previously deposited sand and re-entrained and re-deposited them, with a signature lag surface at the top of this horizon [45]. One of the most important of these types of significant features is the Maximum Flooding Surface (MFS), which defines the boundary between the underlying Transgressive Systems Tract (TST) from the overlying Highstand Tract (HST). The MFS is a condensed section in the stratigraphic column that is typically thin, fossiliferous and may contain phosphatic or glauconitic material that developed during a time of very slow sedimentation when the relative sea level was at its highest [45]. As the eustasic curve is an oscillation between most basinward and most landward, there should be a corresponding time during which there is a turnaround from the most landward projection of the relative sea level back towards the basin. Theoretically, this maximum should also have a physical signature that is recorded in the rock record. In the original model, the Regressive Systems Tract (RST) is composed of continental facies that are fairly unremarkable. There is not much that is distinctive about the depositional environment from which these strata are developed – there is little variation throughout the environment to indicate a distance or proximity to the shoreline. It is this author's opinion that the time of maximum regression is preserved within the sediments, but the depositional environment is not linked directly enough to the changes in relative sea level to leave a distinct, identifiable imprint. Thus, there is no unique physical evidence for the maximum regression in the original model.

Aeolian Systems

The concept of aeolian sequence stratigraphy is based on a fundamental assumption that it is governed by the sediment conservation equation - the net result of fluxes into and out of the system [46]. Influx is a function of the external sediment supply and transport capacity of the wind, and outflux is controlled by spatial and temporal changes in the system's volume, such as an increase in the desert area or a reduction in accommodation. A depositional surface in this system separates retained sediment from that of sediment in transport. This surface rises over time when the sediment budget is positive (influx > outflux), with the positive amount of sediment being held in the system as an accumulation. If there is a change in this balance, and the sediment budget is either neutral (influx = outflux) or negative (influx < outflux), it results in two types of surfaces, a bypass or an erosional super-bounding surface, respectively. In this latter case, a "super surface" is the equivalent to a siliciclastic bounding surface that defines sequences.

One of the main variables in aeolian systems is whether or not the dune field was dry or wet, with the moisture being supplied by groundwater [46-49]. In wet dunes, where the water table is relatively near the surface, capillary action takes moisture almost to the top of the dunes. As a result, these dunes are more likely to be preserved almost intact, as the moisture locks the sediment to the dune and prevents removal by wind. This behavior determines how much surface deflation occurs and thus how thick a preserved dune will be [50]. In other words, the majority of the thickness of a wetted dune will be preserved, resulting in a thicker bed than a similar-sized dry dune. Additionally, moisture retards the development of large avalanche faces results in lower internal dip angles (below 20 degrees) than in dry dunes [51-53].

In dry dunes, the typical internal bedding angles are fairly steep, ranging from 30 up to a max of 36 degrees [51, 53, 54]. This sets up a direct relationship between internal dip angles to the proximity to the local height of the water table and the moisture content of the sediments.

Materials and Methods:

Data were taken from eight drill core from various sections in the T16N R72W block, specifically sections numbered 8, 10, 14, 18, 20, 22, 28 and 32, and four outcrop sections in the Laramie Range, southeastern WY (Figure II-1a). The drill core are part of a collection from the Alcoa Cement Corporation that was donated to the University of Wyoming's Department of Geology and Geophysics in the 1980s.

Ninety-three thin sections were obtained from the drill core, with the majority taken from the most complete drill core, #20-25. Carbonate thin sections were stained with alizaran red-s to facilitate the differentiation between two groups of minerals - aragonite-calcite-witherite-cerussite, stained, and dolomite-siderite-magnesite-rhodochrosite, unstained [55]. All thin sections were studied using standard optical petrography to determine grain size and type, maturity, and semi-quantitative percentages of mineral composition, cement, matrix and number and type of fossils (if present). Silicic lithofacies were assigned names using the Williams et al. [56] classification system, and carbonate lithofacies were named using the Folk [57] classification system. From the descriptions of these thin sections and the outcrop data, seven lithofacies were defined. There is an up-section progression from a basal unconformity through a transitional marine to terrestrial facies which grades upwards into aeolian beds. From these, the formation grades from terrestrial to marine facies and upwards into a series of carbonate beds which then are capped by another unconformity (Figure 3). The facies of interest for this particular study were the ones that are interpreted as aeolian strata.

Results:

Once the existence of aeolian strata was established, additional field data were obtained to determine internal dip angles in these units. Three sub-units in the cross-bedded strata were identified based on erosional surfaces separating them. The lowermost layers averaged approximately 15 degrees, the middle layers typically exhibited approximately 28 degrees and the uppermost layers had approximately 15 degree angles for the internal laminae. This change in the inflection of the cross bedding from lower to higher and back down to lower was found in all outcrops that exhibited the aeolian facies. The layers underlying the lowermost aeolian units were typically deformed, exhibiting convoluted bedding and some (rare) fluid escape structures.

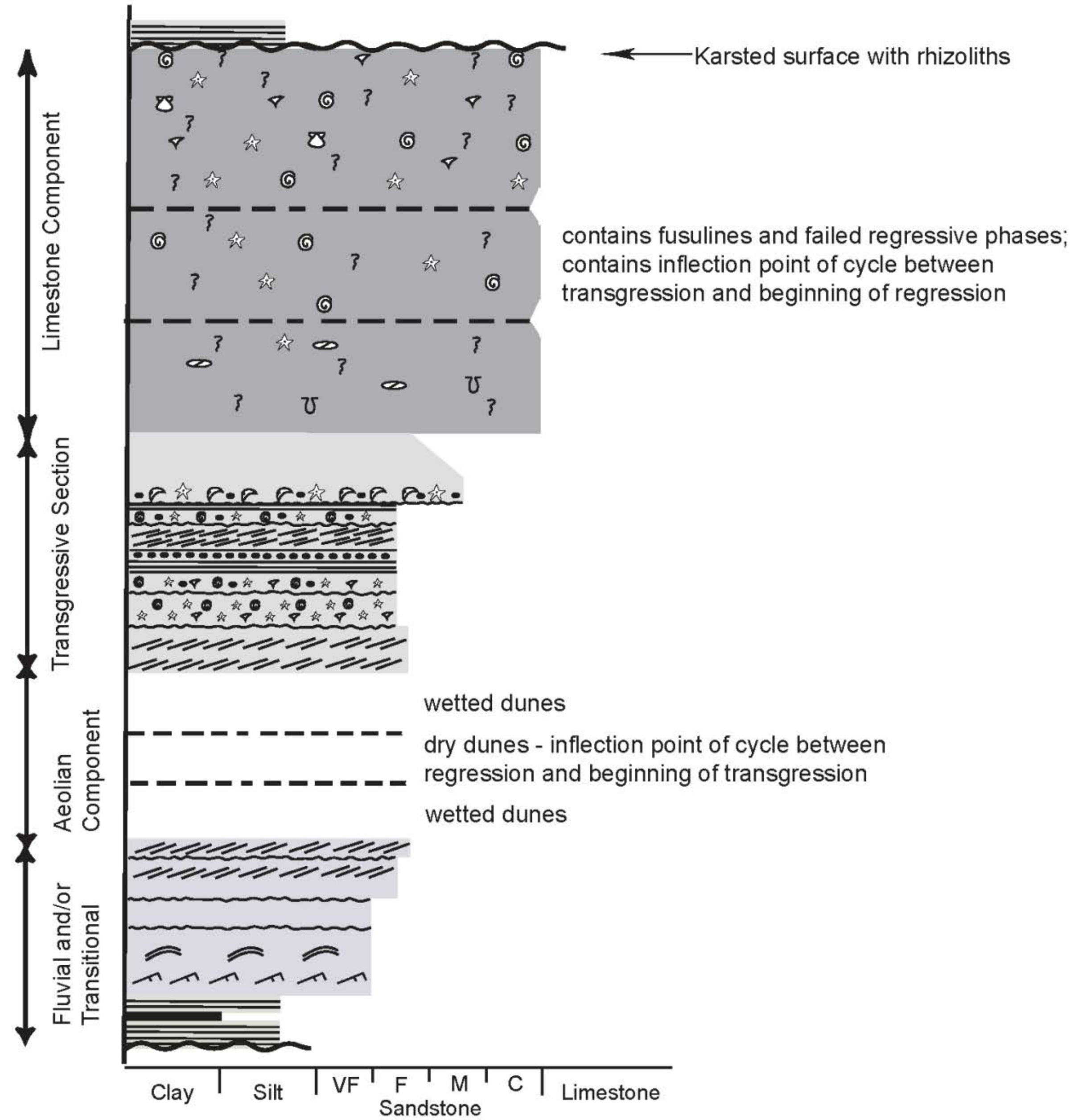

Figure 3: Idealized stratal column of the Casper Formation facies depicting the expected lower angle cross beds in wetted dunes at the top and bottom of the Aeolian Component of the model with the middle section aligning with dry dunes – the point where the Maximum Regressive Surface lies.

Discussion:

The data for the terrestrial sandstone units is interpreted to indicate an aeolian origin. The units exhibited a lack of a calcareous matrix, were dominated by quartz in the grain population and were cross-bedded throughout, with features such as subcritically climbing ripples. No frosting of quartz grains was observed, although this may be as a result of diagenesis given the age of the strata. The observed structures, specifically the massive parallel laminations and the subcritically climbing translatent strata, however, do support the aeolian interpretation. The parallel nature of the cross-bedding's internal laminations and the lack of internal grading within the laminae indicate these are grainfall deposits [58], and the subcritically climbing structures are developed from wind ripple migration [59]. The tabular shape of the unit suggests it was developed from relatively straight-crested dunes [60], while the limited spread of bedding attitudes indicates transverse dunes [61]. The paleodunes are interpreted as individual, simple bedforms, as is indicated by the lack of superimposed forms and internal erosional surfaces, which is typical of an aeolian environment with a constant, unidirectional wind direction [62].

The transition from lower-angled cross beds to higher-angled and back to lower-angled suggests a succession of wetted dunes to dry dunes and back again. This interpretation is based upon the concept of a difference between internal bedding angles of wet versus dry dunes that was specifically explored by Ahlbrandt [63] and supported by related findings in studies such as the ones by Yaalon and Laronne [51], Steidtmann [52], and Grotzinger et al. [53]. In a wet dune, only the uppermost part of the crest is formed of dry sand with an active slip-face that develops characteristic angle-of-repose bedding. The remainder of the dune, approximately 90% of it, is composed of moist sand that is being transported laterally downwind parallel to the lee face and typically produces lower angle bedding, with downwind dips between 14 and 18 degrees. The cohesiveness of the moist sand retards the development of slip-faces and, as a result, the dominant type of internal structure in wet dunes is low-angled bedding. These moist conditions can fluctuate, resulting in dunes that are temporarily dry and permitting the development of active slip-faces [63]. This is thought to have occurred during deposition of the aeolian sediments of the Casper Formation as a result in changes in relative sea level and interpreted to correspond to the turn-around point from offshore regression to onshore transgression. In the original siliciclastic sequence stratigraphy model [1], the authors conjecture that this maximum regressive surface exists, although no physical evidence or characteristics were presented to support this theory. Subsequent examinations of similar siliciclastic sequence stratigraphy models produce the same result, that there should be such a surface but no evidence in the siliciclastic sequences exist that would correspond to it [2, 61, 65, 66]. This seems logical given the dynamics of a siliciclastic system – either the depositional environment does not lend itself to the preservation of a unique signature of the change, or the surface might have been developed, but its characteristics have been subsequently obliterated by erosion during relative sea level fall [45]. In the Casper Formation, because of the different types of juxtaposed depositional environments and related dynamics, it is believed that this turnaround point has been preserved in the record of the transition from wetted to drier to wetted dunes. Similar evidence for preservation of a maximum regressive surface has previously been observed in a few purely aeolian sequence stratigraphic studies [6, 67] but none have been reported for mixed carbonate/aeolian systems.

Soft-sediment deformation is typical of loading on wetted deposits [68], as the added weight of new sediment on wet, previously deposited material causes internal failure of developed structures. As such, the presence of deformed strata in the bottom portion of this facies demonstrates that it was wet prior to deposition of the overlying material, thus supporting the interpretation that the system shifted from wetted dunes to dry. Soft-sediment deformation can be developed in a variety of depositional environments, but it is typical of an aeolian system where sand is moist but not saturated [69].

Conclusion:

The presence of preserved aeolian units within a stratal sequence may contain evidence of a Maximum Regressive Surface in the form of an up-section change from low-angled internal laminae to high-angled and then back to low-angle bedding. This can provide a more complete picture of the eustatic changes during the time during which the sediments were deposited than just having evidence for the time of maximum transgression.

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