**IMPACT OF CONTINENTAL MOTION AND DYNAMIC GLACIATIONS ON LOW-
LATITUDE CLIMATE DURING THE CARBONIFEROUS: THE RECORD OF THE
WYOMING SHELF (WESTERN UNITED STATES)**

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ABSTRACT

The dynamic character of the Late Paleozoic Ice Age is evident from glacial deposits, but its impact on tropical climate is not well constrained. Global changes in climate are overprinted on longer-term palaeogeographic variations, resulting in a complex time-space distribution of climate-sensitive lithologies. The significance of such lithologies in Carboniferous successions of the western United States have not been fully explored. In this study, we provide new interpretations for the palaeoclimatic context of the Amsden and Tensleep Formations (Pennsylvanian, Northern Wyoming, USA). The Amsden Formation consists of a basal sandstone member overlain by red siltstones containing pisolites. Very large-scale (~10m) cross-bedding within the basal sandstone indicates deposition in an erg environment. Iron pisoid-rich layers in the overlying member suggest an evolution toward more humid conditions. Persistent arid conditions during the middle Pennsylvanian are suggested by eolian sandstones and calcretes in the overlying Tensleep Formation. These formations were deposited on the karst topography that developed on top of the lower to middle Mississippian Madison Group. Although the development of karstic features implies that humid conditions prevailed during the late Mississippian, evaporites and evidence for early dolomitization within the formation suggest that it was deposited under arid conditions. These relationships argue for a long-term climate evolution from arid to humid during the Mississippian,

and a return to arid conditions during the Pennsylvanian. This trend can be explained by the northward drift from ~15°S to ~12°N. A comparison with contemporaneous records reveals a diachronous evolution across western Pangaea, with the climatic conditions documented on the Wyoming Shelf being reached later in eastern North America. These relationships indicate that plate motion considerably imprint long-term climatic records. Departures from this trend, suggested by the presence of erg deposits in the basal Amsden Formation, record the overprinting of shorter periods of climate change.

KEYWORDS

Carboniferous climate; Low-latitudes; Late Paleozoic Ice Age; Pangaeon drift; Eolian; Pisolitic ironstone

1. INTRODUCTION

The late Paleozoic was a period of major Earth system change (Blakey, 2008; Montañez and Poulsen, 2013). The closure of the Rheic Ocean during the Mississippian resulted in the creation of the supercontinent Pangaea (Nance et al., 2010), replacing an open oceanic gateway with a major mountain chain that extended from the western United States to eastern Europe. This assembly was contemporaneous with the longest icehouse period of the Phanerozoic, the Late Paleozoic Ice Age (LPIA; Crowell, 1978; Frakes et al., 1992; Fielding et al., 2008a).

Studies over the past decade have increasingly emphasized the discontinuous nature of the Ice Age in time and space, documenting in the high-palaeolatitudes the imprint of glacial epochs alternating with non-glacial intervals (Isbell et al., 2003; Fielding et al., 2008b; Gulbranson et al., 2010). Those intervals of global cooling and warming, fluctuating on time scales of 1 to 10 Myrs, are thought to have been controlled by fluctuations in $p\text{CO}_2$ (Montañez et al., 2007). Several recent studies have investigated the imprint of these dynamic changes of global climate on the low-palaeolatitude record (e.g., Feldman et al.,

2005; Bishop et al., 2010; Allen et al., 2011; Koch and Frank, 2011; Eros et al., 2012; Martin et al., 2012). In doing so, they noted the challenges entailed in deconvolving the effects of global climate change from those caused by the latitudinal drift of continental masses (Roscher and Schneider, 2006; Tabor and Poulsen, 2008). Among the recognized trends of palaeoclimate change, the late Pennsylvanian increase in aridity recorded in the palaeotropics is a subject of vigorous debate as to causal mechanisms (Phillips et al., 1974; Cleal and Thomas, 2005; Tabor and Poulsen, 2008; Pochat and Van Den Driessche, 2011; Gulbranson et al., 2015). The late Pennsylvanian has received considerable attention by researchers, while the Mississippian to Middle Pennsylvanian is relatively poorly understood.

Various formations of Carboniferous age have been described in Wyoming, western United States. They contain a considerable range of climate-sensitive lithologies such as coal beds and eolian sandstones (Prince, 1963; Willis, 1959; Blakey et al., 1988). Although some studies have addressed the climatic implications of those lithologies, their scope was limited in time and space, and the possible reasons behind recorded palaeoenvironmental changes were not fully evaluated. Most such studies were, furthermore, conducted at a time when the Late Paleozoic Ice Age was still considered a single, protracted event (Veevers and Powell, 1987). To the best of our knowledge, these data have not yet been compiled into a comprehensive model that allows exploration of the low-latitudinal response to dynamic Gondwanan glaciations.

The aim of this article is to describe the palaeoclimatic indicators preserved in the Carboniferous formations of northern Wyoming, compare them to those found in equivalent formations in surrounding states, and assess the significance of their spatio-temporal distribution. We then review the implications for the temporal evolution of climate in the western United States from the middle Mississippian (Visean) to middle Pennsylvanian (Moscovian), and evaluate the relative roles of latitudinal drift and global climate change on the observed palaeoclimatic trends.

2. GEOLOGICAL SETTINGS AND REGIONAL STRATIGRAPHY

During the Carboniferous, the Wyoming Shelf (Fig. 1) was an area of low-accommodation sediment accumulation (Sloss, 1950). The main depocenter was located to the west during the Mississippian, in a foreland basin associated with the formation of the Antler Orogenic Belt (Rose, 1976; Gutshick et al., 1980) (Fig. 1). Another depocenter was located to the north, where a W-E oriented trough developed during the Mississippian and earliest Pennsylvanian (Big Snowy Trough; Fig. 1) (Perry and Sloss, 1943; Willis, 1959; Maughan, 1984). Attributed to the reactivation of an older, aborted rift structure (Shepard, 1993), this subsiding trough allowed the preservation of middle to upper Mississippian sediments (Fig. 2) (Perry and Sloss, 1943; Willis, 1959; Maughan, 1984). Contemporaneous sediments are also preserved in northern Utah (Sadlick, 1955, 1957; Arnold and Sadlick, 1962; Prince, 1963; Rose, 1976). Sediments of Middle to Upper Mississippian age are, however, generally lacking from the Wyoming Shelf (Fig. 2).

During the Pennsylvanian, intracratonic blocks were uplifted as a far-field response to stresses associated with the Gondwana-Laurussia collision (Kluth and Coney, 1981; Fig. 1). These uplifts were surrounded by narrow belts of coarse, arkosic alluvial sediments shed off the highlands, mainly known today as the Fountain and Maroon Formations (Howard, 1966; Sweet and Soreghan, 2010).

From the Early Tournaisian to Middle Viséan, extensive platform carbonates formed over what then constituted the western margin of the United States (Sonnenfeld, 1996). Known as the Madison Group and equivalents, this thick succession of carbonates was then exposed during the second half of the Mississippian (Sando, 1988).

In northern Wyoming, the Madison Group is overlain by the Amsden and Tensleep Formations (Darton, 1904). The age of the Amsden Formation has been the subject of considerable debate (Agatston, 1954; Gordon and Yochelson, 1975; Sando et al., 1975). The basal member of this formation is the Darwin Sandstone Member (Blackwelder, 1918; Fig. 2), and its origin has been interpreted as fluvial (Todd, 1964), marine (Gorman, 1963), fluvio-marine (Sando et al., 1975), and more recently eolian in some

locations (Kerr et al., 1986). Its barren character has, however, hindered age determination (Sando et al., 1975). Different authors have placed this sandstone member in the middle Mississippian (Sando, 1972), upper Mississippian (Gordon and Yochelson, 1975; Sando et al., 1975), or Pennsylvanian (Agatston, 1954; Burk, 1954) systems.

The Darwin Sandstone Member of the Amsden Formation is overlain by the Horseshoe Shale Member (Mallory, 1967; Fig. 2). It mainly consist of red siltstones and shales, typically forming recessive slopes between the underlying sandstones or limestones and overlying dolomites (Mallory, 1967). It contains numerous lenses of anhydrite and gypsum (Agatston, 1954), sandstone (Mallory, 1967), carbonate (Sando et al., 1975), and pisolitic ironstone (Agatston, 1954; Gorman, 1963; Sando et al., 1975). There is a debate in the literature as to whether this member is entirely Pennsylvanian in age (Morrowan; Agatston, 1954; Burk, 1954; Maughan, 1984), or if deposition started during the late Mississippian and persisted until the early Pennsylvanian (Late Chesterian-Morrowan; Sando et al., 1975).

The Horseshoe Shale Member is overlain by the third and uppermost member of the Amsden Formation, the Ranchester Limestone Member (Mallory, 1967; Fig. 2). This member consists of cherty dolomite with minor shale (Mallory, 1967). In comparison to the underlying members, the age of the Ranchester Limestone Member is well constrained. Fusulinids (*Millerella marblensis* (Agatston, 1954); *Millerella inflecta* (Gorman, 1963)) and conodonts (Barrick, pers. comm.) indicate an early Pennsylvanian (late Morrowan-early Atokan) age.

The Tensleep Formation, being a major hydrocarbon producer, has been the object of considerable attention (Agatston, 1952; Mankiewicz and Steidtmann, 1979; Moore, 1984; Kerr et al., 1986; Kerr and Dott, 1988; Carr-Crabaugh and Dunn, 1996; Hurley et al., 2003). A middle Pennsylvanian (Desmoinesian) age is well documented (Agatston, 1954; Henbest, 1954, 1956) based notably on the fusulinids *Wedekindellina* sp. and *Fusulina* sp.. Others have also documented the presence of rare Missourian (Verville, 1970) and early Permian (Verville, 1957) forms in the southeastern corner of the Bighorn Basin. Early Permian conodonts have also been documented by Rhodes (1963). It is likely,

however, that those were sampled not from the Tensleep Formation, but rather from Asselian to Artinskian carbonate beds that were found unconformably overlying the Tensleep Formation but were distinct from the overlying Middle to Late Permian Phosphoria/Goose Egg Formations (Todd, 1996; Fig. 2). An entirely Desmoinesian age for the Tensleep Formation is also supported by the presence of a carbonate unit yielding *Neognathodus* sp. (Barrick, pers. comm.), that caps the 50m thick succession of eolian sandstones found in the upper part of the formation in the southeastern Pryor Mountains.

3. METHODS

The Amsden and Tensleep Formations are well-exposed along the edges of the Bighorn Mountains in Wyoming and Montana. Detailed sections through these formations were measured at 12 localities. Thicknesses were obtained with a 1.5 m Jacob's staff when possible, or with a laser rangefinder for inaccessible cliff faces. Samples of specific lithologies were thin-sectioned and analyzed using transmitted light microscopy and cathodoluminescence.

Biostratigraphic data (conodonts, fusulinids, and palynomorphs) were obtained from the literature, along with the spatio-temporal distributions of climate-sensitive lithologies. Early Mississippian to late Pennsylvanian palaeolatitudes for the Bighorn Basin were estimated using Matthew Domeier's data for the Gplates 1.3 software (http://www.earthdynamics.org/data/Domeier2014_data.zip).

4. CLIMATIC INDICATORS IN THE PENNSYLVANIAN FORMATIONS OF NORTHERN WYOMING

4.1 DARWIN SANDSTONE MEMBER (AMSDEN FORMATION)

DESCRIPTION

The Darwin Sandstone Member consists of well-sorted, fine-grained quartz arenites. The thickness of this member is highly variable across the study area, ranging from up to 20 meters in the southeastern part of the Bighorn Basin (Tensleep Canyon; Fig. 3) to only a few meters in the vicinity of Dry Medicine Lodge Creek, Shell Canyon, and Sheep Mountain (Fig. 3). It is completely absent in some places, where the Horseshoe Shale Member rests directly on the Madison Group. Where its thickness does not exceed a few meters, it is either massive or exhibits small to medium (10 to 30cm) sets of trough cross-bedding. It commonly fills solution pipes and fractures in the irregular karst surface of the underlying Madison Group. In the vicinity of Tensleep Canyon, this member is considerably thicker and exhibits flat to low-angle stratification, wavy bedding, medium (40 to 70cm) sets of trough cross-bedding, and very large (~10m) sets of planar cross-bedding (Fig. 4). Palaeocurrent direction is unimodal and towards the west-south-west (Fig. 4C).

INTERPRETATION

In the northern part of the study area (Dry Medicine Lodge Creek, Shell Canyon, White Creek Canyon, Dayton, and Sheep Mountain; Fig. 3), the Darwin Sandstone Member was deposited as the result of migrating small dunes. Our current data do not permit differentiation between an aquatic and an eolian origin for those structures. Toward the south (Tensleep Canyon; Fig. 3), sedimentary structures are spectacularly exposed and allow for more detailed palaeoenvironmental interpretations. Structures at the base of the Darwin Sandstone Member in this area consist mainly of flat to low-angle stratification and wavy bedding. They are interpreted to be the result of migrating small wind ripples in a sand sheet environment (cf. Hunter, 1977). The wavy bedding can potentially be explained as the result of occasional wetting of the surface, allowing the development of adhesion ripples (Kocurek and Fielder, 1982). The middle part of the member, consisting of small to medium sets of cross-bedding, is interpreted as the result of migrating, wind-blown dunes. Observed in the upper part of the member, the 10m thick set of planar cross-bedding is interpreted to be the result of grainfall and/or grainflow deposition on the lee slides of large eolian dunes (McKee, 1966; Hunter, 1977). Based on this interpreted succession, we

suggest that the Darwin Sandstone Member records the migration of an erg system through the region from fore-erg environments (sand sheets and small dunes) to central-erg settings (large dunes) (Porter, 1986).

While a fluvial or marine origin for the Darwin Sandstone Member cannot be ruled out where it is thin and poorly exposed (Dry Medicine Lodge Creek, Shell Canyon, White Creek Canyon, Dayton, and Sheep Mountain; Fig. 3), the exposure at Tensleep Canyon implies that at least parts of the Darwin Sandstone Member were formed in an erg environment, suggesting deposition in an arid setting.

4.2 HORSESHOE SHALE MEMBER (AMSDEN FORMATION)

Although a wide range of lithologies has been observed in the Horseshoe Shale Member, only those that are significantly sensitive to climate are documented here.

DESCRIPTION

The first notable facies, the pisolitic ironstone, consists of poorly sorted conglomeratic layers within the red siltstones that dominates the Horseshoe Shale Member (Fig. 5A and B). Two main types of clasts almost exclusively account for the content of those layers (Fig. 5B and C). The first type is red to brown, hematitic clasts the size of which range from a millimeter to several centimeters. The second type consists of yellow to brown pisoids, mostly sub-centimetric in size (Fig. 5C and D). Coating laminae are wavy and crinkly, and their color under plane polarized light range from colorless, yellow, brown and opaque, suggesting the respective presence of possible kaolinite, limonite or goethite, and hematite.

The second facies is relatively uncommon, but has been observed in the northern exposures. It consist of lense-shaped bodies of poorly sorted, variably cross-bedded, calcareous sandstone containing medium to coarse quartz grains, reddened clasts of micritic limestone, and bioclasts.

INTERPRETATION

Interpretations for the depositional environment of the Horseshoe Shale Member range from a wide, restricted lagoon (Sando et al., 1975) to a floodplain setting (Todd, 1964). Most workers, however, agree that the material mostly comes from the reworking of a lateritic regolith that developed on the exposed Madison Group (Todd, 1964; Sando et al., 1975).

Ferruginous pisoids form pedogenically, when the groundwater table was allowed to migrate vertically between annual dry and wet seasons (Nahon et al., 1980; Siehl and Thein, 1989). In such settings, annual changes in redox potential result in alternations between precipitation of iron oxides, oxyhydroxides and clays (Siehl and Thein, 1989). Those pisoid-rich horizons can subsequently be reworked and accumulate as channel fills (Siehl and Thein, 1989; Al-Bassam and Tamar-Agha, 1998). Such pisolitic structures are found today in tropical environments (Nahon et al., 1980), and are used as indicators for warm and humid climate with a marked seasonality when found in the rock record (Al-Bassam and Tamar-Agha, 1998; Reolid et al., 2008).

Considering its coarser-grained nature and its lens-shape bodies, the second facies is interpreted as deposits of small, ephemeral fluvial channels that cut down through the red floodplain deposits. The abundant carbonate grains were likely derived from the underlying Madison Group.

These facies suggest that climate during the deposition of the Horseshoe Shale Member was at least seasonally more humid than it was during the deposition of the underlying lithologies of the Darwin Sandstone Member.

4.3 RANCHESTER LIMESTONE MEMBER (AMSDEN FORMATION) AND TENSLEEP FORMATION

Detailed accounts of the lithological diversity in the upper Amsden Formation and Tensleep Formation are numerous (see Mankiewicz and Steidtmann, 1979; Kerr et al., 1986; Kerr and Dott, 1988; and Shebl, 1995). Herein, we describe the facies that have a bearing on palaeoclimatic reconstruction.

Facies association 1: Erg deposits

214 *DESCRIPTION*

215 Well-sorted, fine-grained, poorly cemented quartz arenites found in the upper part of the Tensleep
216 Formation commonly contain large to very large (2 to 15m) sets of planar cross-bedding (Fig. 6A). They
217 are commonly interbedded with sandstone intervals containing flat stratification (Fig. 6A). Both facies are
218 laterally extensive. Palaeocurrent direction, obtained from cross-bedding, is unimodal towards the south-
219 south-west.

220 *INTERPRETATION*

221 Thick sets of planar cross-bedding are interpreted to be the result of grainfall and/or grainflow deposition
222 on the lee slides of large eolian dunes (McKee, 1966; Hunter, 1977). Intervals dominated by flat
223 stratification are interpreted to be the result of migrating wind ripples, commonly found in sand sheet
224 environments and interdunes (Hunter, 1977). Migration of large dunes and wind ripples away from
225 coasts, requiring a lack of vegetation, is generally considered to take place in arid environment.

226 Facies association 2: Sabkha-like deposits

227 *DESCRIPTION*

228 Dolomitic, moderately to well-sorted, fine-grained quartz arenites and sandy dolomites are abundant in
229 the Tensleep Formation. Chert nodules, commonly exhibiting knobbly cauliflower-like surfaces, are
230 found in such lithologies (Fig. 6B). They are either isolated or grouped along bedding planes.
231 Submillimetric spherulites of chalcedony, both length-fast and length-slow, have been observed in
232 unfossiliferous dolomicritic horizons and calcite-rich, recrystallized beds (Fig. 6C). Their rim typically
233 display shapes reminiscent of those observed in evaporite rosettes (Fig. 6C). Sandy and dolomitic layers
234 containing desiccation cracks are common (Fig. 6D). Dolomitic, quartz arenites locally exhibit wavy,
235 crinkly laminations. The relative abundances of dolomicrite and quartz sand vary considerably between
236 laminations. The size of dolomite crystals, abundantly present in this association, is generally fine (5-
237 15µm), although coarser (50-60µm), non-planar fabrics were observed.

238 *INTERPRETATION*

239 The dolomitic sandstones and sandy dolomites, common in the lower part of the Tensleep Formation, are
240 regarded as having been deposited in sabkha-like, arid environments. Chert nodules with knobby
241 surfaces bear a resemblance to those described by Milliken (1979), who interpreted them to have formed
242 as silica replaced the original calcium sulfates. Length-slow chalcedony, present in the form of
243 spherulites, has also been linked with the replacement of calcium sulfate minerals (Folk and Pittman,
244 1971; Pittman and Folk, 1971). Although not diagnostic in itself, the way silica manifests itself in the
245 succession is consistent with overprinting of calcium sulfates. These different features are commonly
246 present in arid coastlines, where the coupling of high evaporation and low precipitation rates results in the
247 formation of sulfate nodules (Kinsman, 1969; West et al., 1979). The close resemblance of sub-
248 millimetric spherulites to evaporite rosettes, and their presence in unfossiliferous dolomicrite is also
249 suggestive of formation in an evaporative, supratidal environment (see SMF 23 of Flügel, 2004). The
250 development of penecontemporaneous dolomite, whether by direct precipitation or by replacement of an
251 aragonitic precursor, is frequently associated with arid, evaporative environments (Wells, 1962; Curtis et
252 al., 1963; Illing et al., 1965). The very fine grained nature of the dolomite present in this association is
253 consistent with an early formation via evaporation in supratidal, arid environments (Flügel, 2004). The
254 wavy, crinkly alternations between dolomicrite and quartz sand are interpreted to reflect stabilization by
255 microbial mats (Schieber, 1999), commonly found in the intertidal zone of modern arid coastlines
256 (Kendall and Skipwith, 1968; Alsharhan and Kendall, 2003).

257 Facies association 3: Calcretes

258 *DESCRIPTION*

259 The upper member of the Amsden Formation (Ranchester Limestone Member) and the Tensleep
260 Formation contain well-defined horizons characterized by accumulations of dolomicrite. Their thickness
261 range from 10 to 40 centimeters. These accumulations exhibit knobby to prismatic structures (Fig.

6E), Petrographic observations reveal that this facies mainly consists of micrite, silt-sized quartz grains, and millimetric to centimetric intraclasts delimited by circumgranular cracks, as well as and potential alveolar textures.

INTERPRETATION

The micritic, fossil-free character, the well-defined horizontality, the knobby to prismatic structure of peds, and the presence of circumgranular cracks all suggest that these dolomicritic beds were formed via pedogenesis (Esteban and Klappa, 1983; Soil Survey Staff, 1999). The prismatic structure of peds and the presence of circumgranular cracks are both associated with alternating moisture availability, with intermittent dry conditions allowing contraction of the paleosol (Esteban and Klappa, 1983; Soil Survey Staff, 1999). Pedogenic accumulations of secondary carbonates generally form in semi-arid to arid climates (Machette, 1985).

5. DISCUSSION

The range of lithologies preserved in the Carboniferous formations of Northern Wyoming suggests that climate in the western United States changed considerably over that period (Fig. 7). Additional lithologies indicative of palaeoclimatic regimes have been preserved in the surrounding states, notably during Stages without a stratigraphic record in our study area (Fig. 8). The spatio-temporal distribution of those lithologies suggests that well-defined trends of climate change can be inferred from those records.

5.1 TEMPORAL EVOLUTION OF CLIMATE

5.1.1 EARLY TOURNAISIAN TO MIDDLE VISEAN

From the early Tournaisian to middle Visean, carbonates of the Madison Group were deposited on the Wyoming Shelf (Sando, 1988; Sonnenfeld, 1996) (Fig. 8). The presence of facies representing sabkha and evaporative/restricted lagoonal environments, including evidence for early dolomitization, indicates that

climate was arid during that time (Sonnenfeld, 1996). These facies are most common in the middle part of the formation, and to a lesser degree at the base, of the Madison Group (Sequences II, III, and IV of Sonnenfeld (1996)). The abundance of evaporative features decreases toward the upper part of the formation, but they remain present (Sequences V and VI of Sonnenfeld (1996)). Karstic features, developed during relative sea-level drops, are limited at the top of sequences I, II, and III of Sonnenfeld (1996). They are more pronounced in the upper part of the formation (Sonnenfeld, 1996). The decreasing amount of evaporites, and increasing development of karstic features upward through the formation, both suggest a transition from arid to more humid conditions (Sonnenfeld, 1996).

Deposition of the Madison Group eventually terminated during the Middle Visean (Middle Meramecian), when the entire platform was exposed and turned into a vast karst plain (Sando, 1988; Sonnenfeld, 1996; Fig. 8). The Madison Group was deposited during an overall sea-level highstand, postdating the late Devonian phase of the LPIA (Brezinski et al., 2008; Caputo et al., 2008; Isaacson et al., 2008) and predating the onset of major Carboniferous glaciations (Bishop et al., 2009; Fielding and Frank, 2015). There is to this day an active debate as to when large-scale ice-sheets started to form during the Mississippian, indicated by the onset of a clear orbitally-driven cyclicity in the low-palaeolatitudes (Smith and Read, 2000; Wright and Vanstone, 2001; Al-Tawil and Read, 2003; Butts, 2005; Batt et al., 2008; Buggisch et al., 2008; Rygel et al., 2008; Bishop et al., 2009; Barham et al., 2012; Fielding and Frank, 2015). Specifically, many records seem to indicate a substantial cooling phase during the middle to late Visean (Asbian; Wright and Vanstone, 2001; Bishop et al., 2009; Barham et al., 2012; Fielding and Frank, 2015), while others suggest a Serpukhovian age for the major climatic deterioration (Butts, 2005; Batt et al., 2008; Buggisch et al., 2008). Currently thought to be tectonically-induced (Sonnenfeld, 1996), the exposure of the Wyoming Shelf during the Middle Visean seems to predate by a few million years the current estimates for the onset of Gondwanan glaciation. Until more biostratigraphic and radioisotopic ages allow better correlations between all the available records, the possibility of expanding ice sheets in

Gondwana as the cause of the demise of the carbonate factory on the Wyoming Shelf remains contentious.

5.1.2 MIDDLE VISEAN TO LATE SERPUKHOVIAN

The Wyoming Shelf remained a karst plain for most of the period spanning the middle Visean to late Serpukhovian (Sando, 1988; Sonnenfeld, 1996). Maslyn (1977) documented buried karst towers in Central Colorado. Similarity to the modern landscapes of China and Vietnam in terms of types and scale of features suggest that a humid tropical environment prevailed. Deep solution valleys and abundant dolines have also been described (DeVoto, 1988). All of this evidence points towards a shift to more humid conditions recorded in the upper part of the Madison Group, continuing into the second half of the Mississippian.

Other evidence for humid climate conditions during that period is the presence of coal beds in central Montana (Perry and Sloss, 1943; Willis, 1959; Cole and Daniel, 1984) and northeastern Utah (Sadlick, 1955; Prince, 1963), suggesting waterlogged conditions (Fig. 8). The formations consist dominantly of gray to black, locally carbonaceous shales, sandstones, and limestones of interpreted shallow marine to coastal plain origin (Sadlick, 1955; Maughan and Roberts, 1967; Maughan, 1984; Fig. 8). These formations are notable for their rich and exceptionally preserved fauna (Lund and Melton, 1982; Nelson and Tidwell, 1987; Carroll et al., 1991; Mickle, 2011; Lund et al., 2015) and flora (Arnold and Sadlick, 1962; Tidwell, 1967). Gypsum beds are locally present within these successions (Maughan and Roberts, 1967; Maughan, 1984), suggesting that semi-arid to arid conditions could have existed at times.

An alternative time-space framework exist in the literature (Rose, 1976), in which the reddened Horseshoe Shale Member is a contemporaneous, lateral equivalent to these dark/gray shale of the Big Snowy Group, Manning Canyon Formation, and Doughnut Formation (Fig. 9A). The difference in coloration, as well as the preservation of coal beds, would suggest that drainage conditions differed

between the shelf and the trough. In this alternative model (Fig. 9a), those differences are only spatial and can be accounted for by contrasting accommodation rates.

Wilson (1962) and Maughan (1984), however, consider the Horseshoe Shale Member a temporally distinct unit (Fig. 9B). Favored by the authors here, this view is based on the presence of a similar member in Montana, (the Cameron Creek Member) which is clearly distinct from the underlying Big Snowy Group and composed of red mudstones with lenticular beds of limestone and sandstone (Fig. 8 and 9B).

5.1.3 LATE SERPUKHOVIAN TO EARLY BASHKIRIAN?

As previously mentioned, the timing of deposition of the Darwin Sandstone Member is debated. In most studies, it is assumed to be earliest Pennsylvanian in age (Agatston, 1954; Burk, 1954; Tenney, 1966), with a potential onset of deposition during the latest Mississippian (Sando et al., 1975). Some authors have considered it to be an equivalent of the Kibbey Formation in Montana, however, which constitutes the base of the Big Snowy Group and thought to be middle to late Visean in age (Maughan, 1984).

In Eastern Wyoming, the base of the Minnelusa Formation contains a basal sandstone member (Fairbanks Sandstone) that bears characteristics similar to those observed in the Darwin Sandstone Member (Bates, 1955; Ahlbrandt et al., 2003) (Fig. 8). This member has been interpreted as eolian in origin (Ahlbrandt et al., 2003). This member and the Darwin Sandstone Member likely represent one phase of erg development during the latest Mississippian to/or the earliest Pennsylvanian. In contrast to the underlying karsted surface and the overlying Horseshoe Shale Member (and equivalents), these eolian deposits suggest a transition to sustained arid conditions.

5.1.4 EARLY TO MIDDLE BASHKIRIAN

The red siltstones of the Horseshoe Shale Member and its regional equivalents in Montana (Cameron Creek Member; Wilson, 1962; Maughan, 1984), eastern Wyoming (Bates, 1955; Henbest, 1958), and Colorado (Molas Fm.; Henbest, 1958; Evans and Reed, 2007) accumulated from the early to middle Bashkirian. The presence of pisolitic ironstone suggest relatively humid conditions, with a potentially marked seasonality. A humid tropical climate has previously been inferred for this member, mainly based on the abundance of highly weathered feldspars and a dominance of kaolinite in the clay fraction (Todd, 1964). Plant-bearing layers of shale have also been observed (Sando et al., 1975). Coal beds, silicified logs and plant fossils have been documented in the Kerber Formation of Central Colorado, also thought to be early Pennsylvanian in age (Chronic, 1958).

These records indicate that, following the development of the erg(s) that formed the Darwin Sandstone Member and regional equivalents, conditions reversed back to humid (or at least seasonally sub-humid) during the early to middle Bashkirian.

5.1.5 MIDDLE BASHKIRIAN TO MIDDLE MOSCOVIAN

The change from the Horseshoe Shale Member to the Ranchester Limestone Member (uppermost member of the Amsden Formation) is gradational, as indicated by an upward shift from a kaolinite-dominated clay fraction to a dominance of illite (Todd, 1964; Fig. 7). This transition is accompanied by decreased alteration of feldspar grains (Todd, 1964; Fig. 7). The Ranchester Limestone Member consists mainly of cherty dolomites and contains numerous crinoids, brachiopods, fusulinids, conodonts, and bivalves. Similar lithologies and fauna have been described in Montana (Alaska Bench Formation; Maughan, 1984), eastern Wyoming (Upper Amsden Formation; Tenney, 1966), and Utah (Round Valley Limestone; Sadlick, 1955) (Fig. 8). The abundance of marine carbonates across the region has been interpreted to represent a relative highstand of sea-level (Agatston, 1954).

The abundant chert nodules and spherulites of length-slow chalcedony, also observed in the overlying formations, are interpreted on the basis of petrographic characteristics as calcium sulfates that were later replaced by silica (Picard, 1977; Kerr and Dott, 1988; Luebking et al., 2001). These silica-replaced evaporites are analogous to those described by Folk and Pittman (1971) and Pittman and Folk (1971). This group of indicators (kaolinite-to-illite shift, decreasing alteration of feldspars, silica-replaced evaporites) suggest that more arid conditions prevailed during that time, in comparison to slightly older records.

5.1.6 MIDDLE TO LATE MOSCOVIAN

During the middle to late Moscovian (Desmoinesian), high-frequency relative fluctuations of sea-level resulted in the cyclicity observed in the Tensleep Formation and equivalents (Steidtmann, 1974; Driese and Dott, 1984; Kerr and Dott, 1988; Carr-Crabaugh and Dunn, 1996). Those formations contain numerous lithologies or features analogous to those found today in arid, subtropical environments. Such indicators include eolian (dunes and sand sheets) sandstones, calcic paleosols, abundant desiccation cracks, and silica-replaced evaporites. The dolomitization of marine intervals is thought to have happened contemporaneously to sedimentation or very early during burial (Mankiewicz and Steidtmann, 1979), a feature observed today in arid coastlines (Wells, 1962; Curtis et al., 1963; Illing et al., 1965). Based on these observations, arid conditions seem to have persisted during the deposition of the Tensleep Formation and equivalents in surrounding states.

5.1.7 SUMMARY

An overall evolution from arid to more humid conditions, initiated during the early Viséan and extending through the Serpukhovian (Fig. 11), is implied by a range of indicators. The Darwin Sandstone Member and equivalents indicate a period of aridity (Fig. 11). Filling the fissures and karstic features that develop

on top of the Madison Group, these sandstones clearly postdate the development of a vast karst surface (humid setting) and predate the accumulation of the Horseshoe Shale Member and equivalents (humid to sub-humid). Conditions reversed back to humid or sub-humid during the early to middle Bashkirian (Fig. 11). This humid climate may have been strongly seasonal as well, based on the presence of pisolitic ironstone lenses. Aridity increased over the second part of the Bashkirian, and persisted for the rest of the Pennsylvanian (Fig. 11).

There is little doubt other trends of climate change, both on a sub-million year and multi-million year scales, are yet to be recognized. The cyclicity of upper Mississippian formations mentioned in this paper has previously been noted (Prince, 1963; Shepard, 1993). Climate may very well have fluctuated in conjunction with sea-level, in a manner analogous to the fluctuations documented in the late Pennsylvanian and early Permian records (Cecil, 1990; Tandon and Gibling, 1994; Miller et al., 1996; Falcon-Lang et al., 2009; DiMichele et al., 2010; Rosenau et al., 2013; Cecil et al., 2014). The pervasive character of climatic indicators documented herein, however, suggest that such trends would not significantly alter the overall evolution documented in this study.

5.2 DRIVING FACTORS

5.2.1 CONTINENTAL MOTION

The Carboniferous was a tectonically active period (Blakey, 2008; Domeier and Torsvik, 2014a). During the early Mississippian, North America was located in the southern hemisphere in the low-palaeolatitudes (Domeier and Torsvik, 2014a, b; Fig. 10 and 11). The study area was situated in latitudes ranging from ~12°S to ~17°S during the deposition of the Madison Group (Domeier and Torsvik, 2014b; Fig. 10 and 11). Reconstructions invoke a northeastward movement of Laurussia up until the Bashkirian (Domeier and Torsvik, 2014a, b; Fig. 10). By that time, the study area was located around the Equator (Domeier and Torsvik, 2014b; Fig. 10 and 11). A rapid northward drift of Pangaea, by that time including

Laurussia, is thought to have occurred during the Pennsylvanian (Domeier and Torsvik, 2014a, b; Fig. 10 and 11). As a result, the study area reached higher latitudes ($\sim 10^{\circ}\text{N}$) by the time the Tensleep Formation and equivalents were deposited (Domeier and Torsvik, 2014b; Fig. 10 and 11).

One uncertainty in circulation models for the late Paleozoic concerns the position of the Intertropical Convergence Zone (ITCZ), and how its seasonal migrations affected the distribution of tropical precipitations (Kutzbach and Gallimore, 1989; Parrish, 1993). In the case of a relatively definable zone of high precipitation rates in tropical latitudes (as opposed to a loss of distinct climate belts caused by mega-monsoonal climate), the increasing humidity recorded during the Mississippian could have resulted from the northeastward drift of Laurussia (Fig. 10 and 11). The study area would have initially been located below the descending, moisture-deprived limb of the Hadley Cell. As it drifted northward, it would have eventually been situated below the rising, moisture-laden limb of the Hadley Cell. The reverse phenomenon, drifting from $\sim 4^{\circ}\text{S}$ to $\sim 14^{\circ}\text{N}$ during the Pennsylvanian, could account for increasing aridity between the deposition of the Horseshoe Shale and the Tensleep Formation (Fig. 10 and 11). According to current estimates for the latitudinal position of western Pangaea, our interpretations suggest that the most humid climate belt was not located at the Equator, but was instead somewhat located south in a band extending from $\sim 0^{\circ}$ to 12°S . A similar configuration emerged from the work of Tabor et al. (2008), based on the morphologies of paleosols preserved in late Pennsylvanian to Permian successions. These findings are consistent with climate models (Peyser and Poulsen, 2008; Horton et al., 2012). As a result of the asymmetrical distribution of land masses, the wet season would have been lengthier and the mean annual precipitation rate higher in southern low-latitudes (Peyser and Poulsen, 2008; Horton et al., 2012). Although the southern location of such a band could potentially explain why indicators for arid conditions are preserved in the upper Amsden Formation, deposited during the late Bashkirian when the study area is thought to have been located between $\sim 0^{\circ}$ and 4°N , it seems to be at odd with climate models. According to simulations, such latitudes would have at least been wet during North Hemisphere summers (Peyser and Poulsen, 2008; Horton et al., 2012). Although placing the study area within latitudes better suited for

this type of climate (10° to 30°N) would solve this issue, it does not seem realistic to drastically modify current paleogeographic reconstructions, otherwise well documented and established. The answer to this conundrum is likely to be found in either the presence of local geographical controls on climate, such as mountains or epeiric seas, or in the duration and intensity of the wet season in the northern hemisphere.

The impact of Pangaea's motion on the temporal evolution of climate in a given region has previously been explored (Cecil, 1990; Ziegler et al., 2002; Allen et al., 2011). During the Pennsylvanian, the eastern coast of North America was located between 15 and 20° south of this study's localities (Domeier and Torsvik, 2014b), and as such would have reached humid, tropical latitudes at a later time. This is consistent with the trends documented by Cecil (1990) and Allen et al. (2011) (Fig. 12). In these records, lithologies suggestive of persistent humid conditions appear around the late Serpukhovian/early Bashkirian (Cecil, 1990; Allen et al., 2011; Fig. 12).

These indicators tend to disappear or rarify around the Moscovian-Kasimovian boundary (Phillips et al., 1974; Tabor and Poulsen, 2008; Tabor et al., 2008). Due to its location in arid latitudes during the second half of the Pennsylvanian (Domeier and Torsvik, 2014b), the western United States probably did not respond noticeably to the global aridification that is thought to have drastically influenced the tropical basins (Tabor and Poulsen, 2008; Montañez and Poulsen, 2013; Fig. 12).

These long-term changes in palaeogeography cannot, however, account for the fluctuations that appear to have occurred on more intermediate time scales (switch from humid to arid conditions between the exposure of the Madison Group and the deposition of the Darwin Sandstone Member, and from arid to humid and more seasonal conditions between the deposition of the Darwin Sandstone Member and Horseshoe Shale Member) suggested in this study. Other factors, acting on comparable time frames, are required to explain those.

5.2.3 FLUCTUATIONS IN $p\text{CO}_2$ AND ICE SHEETS

Several studies have linked the alternating glacial and non-glacial intervals recorded in Gondwana (Fielding et al., 2008a,b; Gulbranson et al., 2010; Fig. 11) to fluctuating $p\text{CO}_2$ and concomitant changes in ice volume (Montañez et al., 2007; Frank et al., 2008; Birgenheier et al., 2010; Frank et al., 2015). These alternating glacial regimes in the high latitudes are thought to have affected the palaeotropical distribution of precipitation (Montañez et al., 2007; Peyser and Poulsen, 2008). The evidence for fluctuating climatic conditions of the order of 1 or several million years in the palaeotropics is poorly documented relative to the records left by higher frequency changes (Feldman et al., 2005; Allen et al., 2011). A possible explanation for this discrepancy is that those changes were too modest to produce a clear imprint in the rock record.

Using atmospheric circulation models, Peyser and Poulsen (2008) showed that either a rise of atmospheric $p\text{CO}_2$ (from 1 to 8 times present-atmospheric levels) or a decrease in the size of Gondwanan ice sheets would result in drier and warmer low-latitudes, though they do so in two different ways. Waning of ice sheets results in a reduced temperature gradient in the Southern Hemisphere, weakening and shifting the Hadley cell southward (Peyser and Poulsen, 2008). Increasing $p\text{CO}_2$ corresponds to higher surface temperatures and associated high evaporation rates, which results in reduced soil moisture and a depleted source for tropical precipitation (Peyser and Poulsen, 2008). Rising atmospheric levels of CO_2 and concomitant decrease of ice sheet extent would also result in a reorganization of vegetation biomes, including a collapse of tropical rainforests and an expansion of desert ecosystems (Poulsen et al., 2007).

Considering the equatorial position of Wyoming during the deposition of the Darwin Sandstone Member (Fig. 11), a factor other than palaeogeography would arguably be required to explain this period of increased aridity. Drier tropics, resulting from high atmospheric $p\text{CO}_2$ and smaller ice masses, could be associated with the non-glacial intervals documented from the high-palaeolatitudes (Fielding et al., 2008b). The lack of biostratigraphic constraints for this interval unfortunately preclude any reliable correlation between low and high-palaeolatitudes.

500

501 6. CONCLUSIONS

502 The climatic evolution during the Late Paleozoic Ice Age and the low-latitude response to dynamic
503 changes in ice masses are currently the subject of considerable attention. The description and re-
504 evaluation of climatic indicators in the Carboniferous successions of northern Wyoming, paired with a
505 review of records in surrounding states, suggest that climate changed in the western palaeotropics (Fig.
506 11). The overall evolution of climate in the western United States during that period likely involved a
507 combination of long-term changes (of the order of 10My), caused by the motion of continents and their
508 position relative to atmospheric circulation cells, overprinted by changes on a medium-term (order of
509 several My).

510 (1) During the Mississippian, the shift from a restricted carbonate platform to a deeply karsted plain
511 and the preservation of local coal beds in surrounding areas indicate a transition to more humid
512 settings. This transition corresponds to a northeastward drift of Laurussia that may have shifted
513 the location of the study area from underneath the falling limb of the Hadley Cell to a position
514 within the Intertropical Convergence Zone.

515 (2) The opposite trend (shift from kaolinite-rich, pisolitic ironstone-bearing red siltstones to eolian
516 sandstones interbedded with sabkha deposits and calcretes) is observed in the Lower to Middle
517 Pennsylvanian formations. This shift can also be explained by the northward drift of Pangaea
518 inferred for this period.

519 (3) The Darwin Sandstone Member and equivalents were deposited, at least in some localities, in an
520 erg environment, when the Western United States was situated around the Equator and should
521 have experienced a humid climate. This period of aridity, allowing the migration and deposition
522 of eolian dunes, is best explained by global changes in climate, such as the alternations between
523 glacial epochs and non-glacial intervals documented in the high-latitudes. More detailed

524 biostratigraphic constraints are required to precisely correlate the record described in this study
525 with other low-latitude and high-latitude records.

526 A comparison with contemporaneous records from eastern North America (Appalachian Basin and
527 Maritimes Basin) reveals a diachronous evolution of climate across western Pangaea. Humid conditions
528 prevailed over the Wyoming Shelf during the late Mississippian. These conditions were reached later
529 during the Pennsylvanian in eastern North America, enabling the development of “coal forests”. The close
530 relationship between these trends and Pangaea’s northward motion suggest that these long-term changes
531 were controlled by palaeogeography. These relationships confirm that plate motion should be considered
532 in climatic interpretations of long-term stratigraphic records.

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542 REFERENCES

- 543 Agatston, R.S., 1952, Tensleep Formation of the Big Horn Basin, Wyoming Geological Association
544 Guidebook, Seventh Annual Field Conference, p. 44-48.
- 545 Agatston, R.S., 1954, Pennsylvanian and Lower Permian of northern and eastern Wyoming, American
546 Association of Petroleum Geologists Bulletin, v. 38, p. 508-583

547 Ahlbrandt T.S., Clayton, J.L., and Schenk, C.J., 2003, Climate controls on petroleum systems: The
 548 Pennsylvanian of Eastern Wyoming, U.S.A., and the “sinking reservoir” model, in Cecil, C.B., Edgar,
 549 N.T. (Eds.), *Climate Controls on Stratigraphy*, Society for Economic Paleontologists and Mineralogists,
 550 Special Publication, 77, 239-270

551 Al-Bassam, K.S., and Tamar-Agha, M.Y., 1998, Genesis of the Hussainiyat ironstone deposit, Western
 552 Desert, Iraq, *Mineralium Deposita*, 33(3), 266-282. doi: 10.1007/s001260050146

553 Al-Tawil, A., and Read, J.F., 2003, Late Mississippian (Late Meramecian–Chesterian) glacioeustatic
 554 sequence development on an active distal foreland ramp, Kentucky, U.S.A, in Ahr, W.M., Harris, P.M.,
 555 Morgan, W.A., Somerville, I.D. (Eds.), *Permo-Carboniferous Carbonate Platforms and Reefs*, Society for
 556 Economic Paleontologists and Mineralogists, Special Publication, 78, 33–54

557 Alsharhan, A.S., and Kendall, C.G.St.C., 2003, Holocene coastal carbonates and evaporites of the
 558 southern Arabian Gulf and their ancient analogues, *Earth-Science Reviews*, 61(3), 191-243. doi:
 559 10.1007/s001260050146

560 Allen, J.P., Fielding, C.R., Gibling, M.R., and Rygel, M.C., 2011, Fluvial response to paleo-equatorial
 561 climate fluctuations during the late Paleozoic ice age, *Geological Society of America Bulletin*, 123(7-8),
 562 1524-1538, doi: 10.1130/B30314.1

563 Arnold, C.A., and Sadlick, W., 1962, A Mississippian flora from northeastern Utah and its faunal and
 564 stratigraphic relations, *Contributions from the University of Michigan Museum of Paleontology*, 27 (11),
 565 241– 263

566 Barham, M., Murray, J., Joachimski, M.M., and Williams, D.M., 2012, The onset of the Permo-
 567 Carboniferous glaciation: reconciling global stratigraphic evidence with biogenic apatite $\delta^{18}\text{O}$ records in
 568 the late Viséan, *Journal of the Geological Society*, 169(2), 119-122, doi: 10.1144/0016-76492011-102

569 Bates, R.L., 1955, Permo-Pennsylvanian Formations Between Laramie Mountains, Wyoming, and Black
570 Hills, South Dakota, American Association of Petroleum Geologists Bulletin, 39(10), 1979-2002.

571 Batt, L.S., Pope, M.C., Isaacson, P.E., Montañez, I.P., and Abplanalp, J., 2008, Upper Mississippian
572 Antler foreland basin carbonate and siliciclastic rocks, east-central Idaho and southwestern Montana,
573 USA: distinguishing tectonic and eustatic controls on deposition, Controls on Carbonate Platform and
574 Reef Development, Society for Economic Paleontologists and Mineralogists, Special Publication, 89,
575 147-170,

576 Behnken, F.H., Wardlaw, B.R., and Stout, L.N., 1986, Conodont biostratigraphy of the Permian Meade
577 Peak phosphatic shale member, Phosphoria Formation, southeastern Idaho, Rocky Mountain Geology,
578 24(2), 169-190.

579 Birgenheier, L.P., Frank, T.D., Fielding, C.R., and Rygel, M.C., 2010, Coupled carbon isotopic and
580 sedimentological records from the Permian system of eastern Australia reveal the response of atmospheric
581 carbon dioxide to glacial growth and decay during the late Palaeozoic Ice Age, Palaeogeography,
582 Palaeoclimatology, Palaeoecology, 286(3), 178-193. doi: 10.1016/j.palaeo.2010.01.008

583 Bishop, J.W., Montañez, I.P., Gulbranson, E.L., and Brenckle, P.L., 2009, The onset of mid-
584 Carboniferous glacioeustasy: Sedimentologic and diagenetic constraints, Arrow Canyon, NV,
585 Palaeogeography, Palaeoclimatology, Palaeoecology, v. 276, p. 217–243, doi:
586 10.1016/j.palaeo.2009.02.019

587 Bishop, J.W., Montañez, I.P., and Osleger, D.A., 2010, Dynamic Carboniferous climate change, Arrow
588 Canyon, Nevada, Geosphere, 6(1), 1-34, doi: 10.1130/GES00192.1

589 Bissell, H.J., 1964, Lithology and petrography of the Weber Formation in Utah and Colorado, Guidebook
590 of the geology and mineral resources of the Uinta Basin, Intermountain Association of Petroleum
591 Geologists 13th Field Conference, p. 67-91

592 Bissell, H.J., and Childs, O.E., 1958, The Weber Formation of Utah and Colorado, Symposium on
 593 Pennsylvanian rocks of Colorado and adjacent areas, Rocky Mountain Association of Geologists
 594 Guidebook, p. 26-30.

595 Blackwelder, E., 1918, New geological formations in western Wyoming, Journal of the Washington
 596 Academy of Sciences, 8, 417-426.

597 Blakey, R.C., 2008, Gondwana paleogeography from assembly to breakup—A 500 my odyssey,
 598 Geological Society of America Special Papers, 441, 1-28. doi: 10.1130/2008.2441(01)

599 Blakey, R.C., Peterson, F., and Kocurek, G., 1988, Synthesis of late Paleozoic and Mesozoic eolian
 600 deposits of the Western Interior of the United States, Sedimentary Geology, 56(1), 3-125, doi:
 601 10.1016/0037-0738(88)90050-4

602 Brezinski, D.K., Cecil, C.B., Skema, V.W., and Stamm, R., 2008, Late Devonian glacial deposits from
 603 the eastern United States signal an end of the mid-Paleozoic warm period, Palaeogeography,
 604 Palaeoclimatology, Palaeoecology, 268(3), 143-151, doi:10.1016/j.palaeo.2008.03.042

605 Buggisch, W., Joachimski, M.M., Sevastopulo, G., and Morrow, J.R., 2008, Mississippian $\delta^{13}\text{C}_{\text{carb}}$ and
 606 conodont apatite $\delta^{18}\text{O}$ records—their relation to the Late Palaeozoic Glaciation, Palaeogeography,
 607 Palaeoclimatology, Palaeoecology, 268(3-4), 273-292, doi: 10.1016/j.palaeo.2008.03.043

608 Burk, C.A., 1954, Faunas and age of the Amsden Formation in Wyoming, Journal of Paleontology, 28, 1-
 609 16.

610 Butts, S.H., 2005, Latest Chesterian (Carboniferous) initiation of Gondwanan glaciation recorded in
 611 facies stacking patterns and brachiopod paleocommunities of the Antler foreland basin, Idaho,
 612 Palaeogeography, Palaeoclimatology, Palaeoecology, 223(3), 275-289, doi: 10.1016/j.palaeo.2005.04.010

613 Caputo, M.V., de Melo, J.H.G., Streel, M., and Isbell, J.L., 2008, Late Devonian and early Carboniferous
614 glacial records of South America, Geological Society of America Special Papers, 441, 161-173. doi:
615 10.1130/2008.2441(11)

616 Carroll, R.L., Bybee, P., and Tidwell, W.D., 1991, The oldest microsauro (Amphibia), Journal of
617 Paleontology, 65, 314-322

618 Carr-Crabaugh, M., and Dunn, T.L., 1996, Reservoir heterogeneity as a function of accumulation and
619 preservation dynamics, Tensleep Sandstone, Bighorn and Wind River basins, Wyoming, in Longman,
620 M.W. and Sonnenfeld, M.D., eds., Paleozoic systems of the Rocky Mountain region, Denver, Colorado,
621 Rocky Mountain Section, Society for Sedimentary Geology, p. 305–320.

622 Cecil, C.B., 1990, Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks,
623 Geology, 18, 533-536. doi: 10.1130/0091-7613(1990)018<0533:PCOSRO>2.3.CO;2

624 Cecil, C.B., DiMichele, W.A., and Elrick, S.D., 2014, Middle and Late Pennsylvanian cyclothems,
625 American Midcontinent: Ice-age environmental changes and terrestrial biotic dynamics, Comptes Rendus
626 Geoscience, 346(7), 159-168. doi: 10.1016/j.crte.2014.03.008

627 Cleal, C.J., and Thomas, B.A., 2005, Palaeozoic tropical rainforests and their effect on global climates: is
628 the past the key to the present?, Geobiology, 3 (1), 13-31, doi: 10.1111/j.1472-4669.2005.00043.x

629 Cole, G.A., and Daniel, J.A., 1984, Thermal maturity trends of the Heath Formation, in J. Woodward, F.
630 Meissner, and J.L. Clayton, eds, Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky
631 Mountain Association of Geologists, p. 275-280.

632 Cox, R.S., 1986, Preliminary report on the age and palynology of the Bear Gulch Limestone
633 (Mississippian, Montana), Journal of Paleontology, 60, 952-956.

634 Chronic, B.J.Jr., 1958, Pennsylvanian rocks in central Colorado, in Symposium on Pennsylvanian rocks
635 of Colorado and adjacent areas, Denver, Rocky Mountain Association of Geologists, p. 59-63.

636 Crowell, J.C., 1978, Gondwanan glaciation, cyclothems, continental positioning, and climate change,
637 American Journal of Science, 278(10), 1345-1372.

638 Curtis, R., Evans, G., Kinsman, D.J.J., and Shearman, D.J., 1963, Association of dolomite and anhydrite
639 in the recent sediments of the Persian Gulf, Nature, 197, 679-680. doi: 10.1038/197679a0

640 Darton, N.H., 1904, Comparison of the stratigraphy of the Black Hills, Bighorn Mountains, and Rocky
641 Mountain Front Range, Geological Society of America Bulletin, v. 15, p. 379-448. doi: 10.1130/GSAB-
642 15-379

643 DeVoto, R.H., 1988, Late Mississippian paleokarst and related mineral deposits, Leadville Formation,
644 central Colorado, in: James, N.P., Choquette, P.W. (Eds.), Paleokarst, Springer-Verlag, New York, pp.
645 278–305.

646 DiMichele, W.A., Cecil, C.B., Montañez, I.P., and Falcon-Lang, H.J., 2010, Cyclic changes in
647 Pennsylvanian paleoclimate and effects on floristic dynamics in tropical Pangaea, International Journal of
648 Coal Geology, 83(2), 329-344. doi: 10.1016/j.coal.2010.01.007

649 Domeier, M., and Torsvik, T.H., 2014a, Plate tectonics in the Late Paleozoic, Geoscience Frontiers 5,
650 303-350. doi: 10.1016/j.gsf.2014.01.002

651 Domeier, M., and Torsvik, T.H., 2014b, 410-250Ma Gplates model ([http://www.](http://www.earthdynamics.org/data/Domeier2014_data.zip)
652 [earthdynamics.org/data/Domeier2014_data.zip](http://www.earthdynamics.org/data/Domeier2014_data.zip))

653 Driese, S.G., and Dott, R.H.Jr., 1984, Model for sandstone-carbonate “cyclothems” based on upper
654 member of Morgan Formation (Middle Pennsylvanian) of Northern Utah and Colorado, American
655 Association of Petroleum Geologists Bulletin, 68(5), 574-597.

656 Eros, J.M., Montañez, I.P., Osleger, D.A., Davydov, V.I., Nemyrovska, T.I., Poletaev, V.I., and
657 Zhykalyak, M.V., 2012, Sequence stratigraphy and onlap history of the Donets Basin, Ukraine: insight

658 into Carboniferous icehouse dynamics, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 313, 1-25,
 659 doi: 10.1016/j.palaeo.2011.08.019

660 Esteban, M., and Klappa, C.F., 1983, Subaerial exposure environments, In: Scholle, P.A., Bebout, D.G.,
 661 Moore, C.H. (Eds.), *Carbonate Depositional Environments.*, American Association of Petroleum
 662 Geologists Memoir, Tulsa, OK, vol. 33, pp. 1 – 96. Evans, J.E., and Reed, J.M., 2007, Integrated loessite-
 663 paleokarst depositional system, early Pennsylvanian Molas formation, Paradox Basin, southwestern
 664 Colorado, USA, *Sedimentary Geology*, 195(3), 161-181, doi:10.1016/j.sedgeo.2006.07.010

665 Falcon-Lang, H.J., Nelson, W.J., Elrick, S., Looy, C.V., Ames, P.R., and DiMichele, W.A., 2009, Incised
 666 channel fills containing conifers indicate that seasonally dry vegetation dominated Pennsylvanian tropical
 667 lowlands, *Geology*, 37 (10), 923-926. doi: 10.1130/G30117A.1

668 Feldman, H.R., Franseen, E.K., Joeckel, R.M., and Heckel, P.H., 2005, Impact of longer-term modest
 669 climate shifts on architecture of high-frequency sequences (cyclothems), Pennsylvanian of Midcontinent
 670 USA, *Journal of Sedimentary Research*, 75 (3), 350-368, doi: 10.2110/jsr.2005.028

671 Fielding, C.R., Frank, T.D., and Isbell, J.L., 2008a, The late Paleozoic ice age—a review of current
 672 understanding and synthesis of global climate patterns, *Geological Society of America Special Paper*,
 673 441, 343-354, doi: 10.1130/2008.2441(24)

674 Fielding, C.R., Frank, T.D., Birgenheier, L.P., Rygel, M.C., Jones, A.T., and Roberts, J., 2008b,
 675 Stratigraphic imprint of the Late Palaeozoic Ice Age in eastern Australia: a record of alternating glacial
 676 and nonglacial climate regime, *Journal of the Geological Society of London*, 165 (1), 129-140, doi:
 677 10.1144/0016-76492007-036

678 Fielding, C.R., and Frank, T.D., 2015, Onset of the glacioeustatic signal recording late Paleozoic
 679 Gondwanan ice growth: new data from paleotropical East Fife, Scotland, *Palaeogeography*,
 680 *Palaeoclimatology, Palaeoecology*, 426, 121-138. doi: 10.1016/j.palaeo.2015.03.002

681 Flügel, E., 2004, *Microfacies of carbonate rocks: analysis, interpretation and application*, Springer.

682 Folk, R.L., and Pittman, J.S., 1971, Length-slow chalcedony: a new testament for vanished evaporites,
683 *Journal of Sedimentary Research*, 41(4), 1045-1058. doi: 10.1306/74D723F1-2B21-11D7-
684 8648000102C1865D

685 Frakes, L.A., Francis, J.E., and Syktus, J.I., 1992, *Climate modes of the Phanerozoic*, Cambridge
686 University Press.

687 Frank, T.D., Birgenheier, L.P., Montañez, I.P., Fielding, C.R., and Rygel, M.C., 2008, Late Paleozoic
688 climate dynamics revealed by comparison of ice-proximal stratigraphic and ice-distal isotopic records,
689 *Geological Society of America Special Papers*, 441, 331-342. doi: 10.1130/2008.2441(23)

690 Frank, T.D., Shultis, A.I., and Fielding, C.R., 2015, Acme and demise of the late Palaeozoic ice age: A
691 view from the southeastern margin of Gondwana, *Palaeogeography, Palaeoclimatology, Palaeoecology*,
692 418, 176-192. doi: 10.1016/j.palaeo.2014.11.016

693 Frenzel, H., and Mundorff, M., 1942, Fusulinidae from the Phosphoria Formation of Montana, *Journal of*
694 *Paleontology*, 16, 675-684.

695 Fryberger, S.G., 1984, The Permian Upper Minnelusa Formation, Wyoming; ancient example of an
696 offshore prograding eolian sand sea with geomorphic facies, and system-boundary traps for petroleum,
697 *Wyoming Geological Association Guidebook*, 35, 241–271.

698 Gordon, M.Jr., and Yochelson, E.L., 1975, *Gastropoda, Cephalopoda, and Trilobita of the Amsden*
699 *Formation (Mississippian and Pennsylvanian) of Wyoming*, U.S. Geological Survey Professional Paper
700 848-F, 30 p.

701 Gorman, D.R., 1963, *Stratigraphic-sedimentational aspects of the Amsden Formation: Big Horn*
702 *Mountains, Wyoming*, Wyoming Geological Association/Billings Geological Society Guidebook, p. 67–
703 70.

704 Gradstein, F.M., Ogg, G., and Schmitz, M., 2012, The Geologic Time Scale 2012, Elsevier

705 Gulbranson, E.L., Montañez, I.P., Schmitz, M.D., Limarino, C.O., Isbell, J.L., Marensi, S.A., and
706 Crowley, J. L., 2010, High-precision U-Pb calibration of Carboniferous glaciation and climate history,
707 Paganzo Group, NW Argentina, Geological Society of America Bulletin, 122(9-10), 1480-1498, doi:
708 10.1130/B30025.1

709 Gulbranson, E.L., Montañez, I.P., Tabor, N.J., and Limarino, C.O., 2015, Late Pennsylvanian
710 aridification on the southwestern margin of Gondwana (Paganzo Basin, NW Argentina): A regional
711 expression of a global climate perturbation, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 417,
712 220-235, doi: 10.1016/j.palaeo.2014.10.029

713 Gutshick, R.C., Sandberg, C.A., and Sando, W.J., 1980, Mississippian shelf margin and carbonate
714 platform from Montana to Nevada, in Fouch, T.D., Magathan, E.R. (Eds.), *Paleozoic Paleogeography of*
715 *West-central United States*, Society for Economic Paleontologists and Mineralogists Rocky Mountain
716 Section, pp. 111 – 128.

717 Henbest, L.G., 1954, Pennsylvanian foraminifera in Amsden Formation and Tensleep Sandstone, Montana
718 and Wyoming, Billings Geological Society Guidebook, 5th Annual Field Conference, p.50-53,

719 Henbest, L.G., 1956, Foraminifera and correlation of the Tensleep Sandstone of Pennsylvanian age in
720 Wyoming, Wyoming Geological Association Guidebook, 11th Annual Field Conference, p.58-63,

721 Henbest, L.G., 1958, Significance of karst terrane and residuum in Upper Mississippian and Lower
722 Pennsylvanian rocks, Rocky Mountain region, in: Powder River Basin, Wyoming Geological Association
723 13th Annual Field Conference Guidebook, p. 36-37.

724 Horton, D.E., Poulsen, C.J., Montañez, I.P., and DiMichele, W.A., 2012, Eccentricity-paced late
725 Paleozoic climate change, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 331, 150-161. doi:
726 10.1016/j.palaeo.2012.03.014

727 Howard, J.D., 1966, Patterns of sediment dispersal in the Fountain Formation of Colorado, *The Mountain*
 728 *Geologist*, v. 3, p. 147–153.

729 Hoyt, J.H., and Chronic, J., 1962, Atokan fusulinids from the Casper Formation, east flank of the Laramie
 730 Mountains, Wyoming, *Journal of Paleontology*, 36, 161-164.

731 Huffman, A.C., 2003, Middle Pennsylvanian tectonics of the conterminous United States, In: Cecil, C.B.
 732 and Edgar, N.T., eds., *Advances in carbonate sequence stratigraphy, application to reservoirs, outcrops*
 733 *and models*, Society for Sedimentary Geology (SEPM), v. 77, p. 73–94.

734 Hunter, R.E., 1977, Basic types of stratification in small eolian dunes, *Sedimentology*, 24(3), 361-387.
 735 doi: 10.1111/j.1365-3091.1977.tb00128.x

736 Hurley, N. F., Aviantara, A.A., and Kerr, D.R., 2003, Structural and stratigraphic compartments in a
 737 horizontal well drilled in the eolian Tensleep Sandstone, Byron field, Wyoming, *American Association of*
 738 *Petroleum Geologists Methods in Exploration Series*, v. 14, p. 143–159.

739 Illing, L.V., Wells, A.J., and Taylor, J.C.M., 1965, Penecontemporary dolomite in the Persian Gulf, in:
 740 Pray, L.C., and Murray, R.C., (Eds), *Dolomitization and Limestone Diagenesis*, Society for Economic
 741 Paleontologists and Mineralogists Special Publication, 13, 89–111.

742 Isaacson, P.E., Diaz-Martinez, E., Grader, G.W., Kalvoda, J., Babek, O., and Devuyt, F.X., 2008, Late
 743 Devonian–earliest Mississippian glaciation in Gondwanaland and its biogeographic consequences,
 744 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 268(3), 126-142, doi:10.1016/j.palaeo.2008.03.047

745 Isbell, J.L., Miller, M.F., Wolfe, K.L., and Lenaker, P.A., 2003, Timing of late Paleozoic glaciation in
 746 Gondwana: Was glaciation responsible for the development of northern hemisphere cyclothems? in Chan,
 747 M.A. and Archer, A.A., eds., *Extreme Depositional Environments: Mega End Members in Geologic*
 748 *Time*. Geological Society of America, Special Papers, 370, 5–24, doi: 10.1130/0-8137-2370-1.5

749 Jennings, T.V., 1959, Faunal zonation of the Minnelusa Formation, Black Hills, South Dakota. *Journal of*
750 *Paleontology*, 33, 986-1000.

751 Katz, D.A., Buoniconti, M.R., Montañez, I.P., Swart, P.K., Eberli, G.P., and Smith, L.B., 2007, Timing
752 and local perturbations to the carbon pool in the lower Mississippian Madison Limestone, Montana and
753 Wyoming, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 256(3), 231-253. doi:
754 10.1016/j.palaeo.2007.02.048

755 Kendall, C.G.St.C., and Skipwith, P., 1968, Recent algal mats of a Persian Gulf lagoon, *Journal of*
756 *Sedimentary Petrology*, 38, 1040-1058. doi: 10.1306/74D71AF5-2B21-11D7-8648000102C1865D

757 Kerr, D.R., and Dott, R.H.Jr., 1988, Eolian dune types preserved in the Tensleep Sandstone
758 (Pennsylvanian-Permian), north central Wyoming, *Sedimentary Geology*, v. 56, p. 383-402. doi:
759 10.1016/0037-0738(88)90062-0

760 Kerr, D.R., Wheeler, D.M., Rittersbacher, D.J., and Home, J.C., 1986, Stratigraphy and sedimentology of
761 the Tensleep Sandstone (Pennsylvanian and Permian), Bighorn Mountains, Wyoming, Wyoming
762 Geological Association Earth Science Bulletin, v. 19, p. 61-77

763 Kinsman, D.J., 1969, Modes of formation, sedimentary associations, and diagnostic features of shallow-
764 water and supratidal evaporites, *American Association of Petroleum Geologists Bulletin*, 53(4), 830-840.

765 Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains, *Geology*, 9(1), 10-
766 15, doi: 10.1130/0091-7613(1981)9<10:PTOTAR>2.0.CO;2

767 Koch, J.T., and Frank, T.D., 2011, The Pennsylvanian–Permian transition in the low-latitude carbonate
768 record and the onset of major Gondwanan glaciation, *Palaeogeography, Palaeoclimatology,*
769 *Palaeoecology*, 308(3), 362-372, doi: 10.1016/j.palaeo.2011.05.041

770 Kocurek, G., and Fielder, G., 1982, Adhesion structures, *Journal of Sedimentary Research*, 52, 1230–
771 1241. doi: 10.1306/212F8102-2B24-11D7-8648000102C1865D

772 Kutzbach, J.E., and Gallimore, R.G., 1989, Pangaeen climates: megamonsoons of the megacontinent,
773 Journal of Geophysical Research, 94, 3341-3357. doi: 10.1029/JD094iD03p03341

774 Love, J.D., and Christiansen, A.C., 1985, Geologic Map of Wyoming, US Geological Survey, scale
775 1:500,000, 3 sheets

776 Luebking, G.A., Longman, M.W., and Carlisle, W.J., 2001, Unconformity-related chert/dolomite
777 production in the Pennsylvanian Amsden Formation, Wolf Springs fields, Bull Mountains basin of central
778 Montana, American Association of Petroleum Geologists Bulletin, 85(1), 131-148.

779 Lund R., and Melton W.G.Jr., 1982, A new actinopterygian fish from the Mississippian Bear Gulch
780 Limestone of Montana, Palaeontology, 25, 485–498

781 Lund, R., Greenfest-Allen, E., and Grogan, E.D., 2015, Ecomorphology of the Mississippian fishes of the
782 Bear Gulch Limestone (Heath formation, Montana, USA), Environmental Biology of Fishes, 98 (2), 739-
783 754. doi: 10.1007/s10641-014-0308-x

784 Machette, M.N., 1985, Calcic soils of the southwestern United States, In D.L. Weide (ed.) Soils and
785 Quaternary Geology of the Southwestern United States, Geological Society of America Special Paper 20,
786 1-21. doi: 10.1130/SPE203-p1

787 Mallory, W.W., 1967, Pennsylvanian and associated rocks in Wyoming, U.S. Geological Survey
788 Professional Paper 554-G, 31 p.

789 Mankiewicz, D., and Steidtmann, J.R., 1979, Depositional environments and diagenesis of the Tensleep
790 Sandstone, eastern Bighorn Basin, Wyoming: Society of Economic Paleontologists and Mineralogists
791 Special Publication 26, p. 319–336.

792 Martin, L.G., Montañez, I.P., and Bishop, J.W., 2012, A paleotropical carbonate-dominated archive of
793 carboniferous icehouse dynamics, Bird Spring Fm., Southern Great Basin, USA, Palaeogeography,
794 Palaeoclimatology, Palaeoecology, 329, 64-82, doi: 10.1016/j.palaeo.2012.02.018

795 Maslyn, R.M., 1977, Fossil tower karst near Molas Lake, Colorado, *The Mountain Geologist*, 14, 17–25.

796 Maughan, E.K., 1984, Paleogeographic setting of Pennsylvanian Tyler Formation and relation to
797 underlying Mississippian rocks in Montana and North Dakota, *American Association of Petroleum*
798 *Geologists Bulletin*, 68(2), 178-195,

799 Maughan, E.K., and Roberts, A.E., 1967, Big Snowy and Amsden groups and the Mississippian-
800 Pennsylvanian boundary in Montana, United States Geological Survey, Professional Paper 554-B, 27 p.

801 McKee, E.D., 1966, Structures of dunes at White Sands National Monument, New Mexico (and a
802 comparison with structures of dunes from other selected areas), *Sedimentology*, 7(1), 3-69. doi:
803 10.1111/j.1365-3091.1966.tb01579.x

804 Mickle, K.E., 2011, The early actinopterygian fauna of the Manning Canyon Shale Formation (upper
805 Mississippian, lower Pennsylvanian) of Utah, USA, *Journal of Vertebrate Paleontology*, 31(5), 962-980.

806 Miller, K.B., McCahon, T.J., and West, R.R., 1996, Lower Permian (Wolfcampian) paleosol-bearing
807 cycles of the US Midcontinent: evidence of climatic cyclicity, *Journal of Sedimentary Research*, 66 (1),
808 71-84. doi: 10.1306/D42682B6-2B26-11D7-8648000102C1865D

809 Milliken, K.L., 1979, The silicified evaporite syndrome -- Two aspects of the silicification history of
810 former evaporite nodules from southern Kentucky and northern Tennessee, *Journal of Sedimentary*
811 *Petrology*, v. 49, p. 245–256. doi: 10.1306/212F7707-2B24-11D7-8648000102C1865D

812 Montañez, I.P., and Poulsen, C.J., 2013, The late Paleozoic ice age: an evolving paradigm, *Annual*
813 *Review of Earth and Planetary Sciences*, 41, 629-656, doi: 10.1146/annurev.earth.031208.100118

814 Montañez, I.P., Tabor, N.J., Niemeier, D., DiMichele, W.A., Frank, T.D., Fielding, C.R., Isbell, J.L.,
815 Birgenheier, L.P., and Rygel, M.C., 2007, CO₂-forced climate and vegetation instability during Late
816 Paleozoic deglaciation, *Science*, 315, 87–91, doi: 10.1126/science.1134207

817 Moore, D.A., 1984, The Tensleep Formation of the southeastern Big Horn basin, Wyoming, in: Goolsby,
818 J., and Morton, D., eds., The Permian and Pennsylvanian geology of Wyoming, Wyoming Geological
819 Association 35th Annual Field Conference Guidebook, p. 273–279.

820 Mundt, P.A., 1956, Heath-Amsden strata in central Montana, American Association of Petroleum
821 Geologists Bulletin, 40(8), 1915-1934,

822 Nahon, D., Carozzi, A.V., and Parron, C., 1980, Lateritic weathering as a mechanism for the generation
823 of ferruginous ooids, Journal of Sedimentary Research, 50(4), 1287-1298. doi: 10.1306/212F7BD5-2B24-
824 11D7-8648000102C1865D

825 Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan,
826 R.A., and Woodcock, N. H., 2010, Evolution of the Rheic Ocean, Gondwana Research, 17 (2), 194-222,
827 doi: 10.1016/j.gr.2009.08.001

828 Nelson, C.R., and Tidwell, W.D., 1987, Brodioptera stricklandi n. sp. (Megasecoptera: Brodiopteridae), a
829 new fossil insect from the Upper Manning Canyon Shale Formation, Utah (Lowermost Namurian B),
830 Psyche, 94, 309-316.

831 Parrish, J.T., 1993, Climate of the supercontinent Pangea, The Journal of Geology, 101, 215-233.

832 Perry, E.S., and Sloss, L.L., 1943, Big Snowy group: Lithology and correlation in the northern Great
833 Plains, American Association of Petroleum Geologists Bulletin, 27(10), 1287-1304.

834 Peyser, C.E., and Poulsen, C.J., 2008, Controls on Permo-Carboniferous precipitation over tropical
835 Pangaea: a GCM sensitivity study, Palaeogeography, Palaeoclimatology, Palaeoecology, 268(3), 181-192.
836 doi: 10.1016/j.palaeo.2008.03.048

837 Picard, M.D., 1977, Petrography and stratigraphy of productive beds in the Morgan Formation, Church
838 Buttes Unit No. 19, southwest Wyoming, in: Rocky Mountain thrust belt geology and resources,
839 Wyoming Geological Association, 29th Annual Field Conference, p.179-196.

840 Pittman, J.S., and Folk, R.L., 1971, Length-slow chalcedony after sulphate evaporite minerals in
841 sedimentary rocks, *Nature*, 230(11), 64-65. doi: 10.1038/physci230064a0

842 Phillips, T.L., Peppers, R.A., Avcin, M.J., and Laughnan, P.F., 1974, Fossil plants and coal: patterns of
843 change in Pennsylvanian coal swamps of the Illinois Basin, *Science*, 184(4144), 1367-1369, doi:
844 10.1126/science.184.4144.1367

845 Pochat, S., and Van Den Driessche, J., 2011, Filling sequence in Late Paleozoic continental basins: A
846 chimera of climate change? A new light shed given by the Graissessac–Lodève basin (SE France),
847 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 302(3), 170-186, doi: 10.1016/j.palaeo.2011.01.006

848 Porter, M.L., 1986, Sedimentary record of erg migration, *Geology*, 14(6), 497-500, doi: 10.1130/0091-
849 7613(1986)14<497:SROEM>2.0.CO;2

850 Poulsen, C.J., Pollard, D., Montañez, I.P., and Rowley, D., 2007, Late Paleozoic tropical climate response
851 to Gondwanan deglaciation, *Geology*, 35 (9), 771-774. doi: 10.1130/G23841A.1

852 Prince, D., 1963, Mississippian coal cyclothems in the Manning Canyon Shale of central Utah, Brigham
853 Young University Geology Studies, 10, 83-103.

854 Raymond, A., and Metz, C., 2004, Ice and its consequences: Glaciation in the Late Ordovician, Late
855 Devonian, Pennsylvanian-Permian, and Cenozoic compared, *The Journal of Geology*, 112 (6), 655-670.

856 Reolid, M., Abad, I., and Martín-García, J.M., 2008, Palaeoenvironmental implications of ferruginous
857 deposits related to a Middle–Upper Jurassic discontinuity (Prebetic Zone, Betic Cordillera, southern
858 Spain), *Sedimentary Geology*, 203(1), 1-16. doi: 10.1016/j.sedgeo.2007.10.001

859 Rhodes, F.H.T., 1963, Conodonts from the Topmost Tensleep Sandstone of the Eastern Big Horn
860 Mountains, Wyoming, *Journal of Paleontology*, v. 37, p. 401-408

861 Roscher, M., and Schneider, J.W., 2006, Permo-Carboniferous climate: Early Pennsylvanian to Late
 862 Permian climate development of central Europe in a regional and global context, Geological Society of
 863 London, Special Publications, 265(1), 95-136. doi: 10.1144/GSL.SP.2006.265.01.05

864 Rose, P.R., 1976, Mississippian carbonate shelf margins, western United States. In: Hill, J.G. (Ed.),
 865 Geology of the Cordilleran Hingeline, Rocky Mountain Association of Geologists, Denver, pp. 135–151,

866 Rosenau, N.A., Tabor, N.J., Elrick, S.D., and Nelson, W.J., 2013, Polygenetic history of paleosols in
 867 middle–upper Pennsylvanian cyclothems of the Illinois basin, USA: Part II. Integrating geomorphology,
 868 climate, and glacioeustasy, *Journal of Sedimentary Research*, 83 (8), 637-668. doi: 10.2110/jsr.2013.51

869 Rygel, M.C., Fielding, C.R., Frank, T.D., and Birgenheier, L.P., 2008, The magnitude of Late Paleozoic
 870 glacioeustatic fluctuations: a synthesis, *Journal of Sedimentary Research*, 78(8), 500-511, doi:
 871 10.2110/jsr.2008.058

872 Sadlick, W., 1955, Carboniferous formations of northeastern Uinta Mountains: Wyoming Geological
 873 Association, 10th Annual Field Conference, p. 49-59,

874 Sadlick, W., 1957, Regional relations of Carboniferous rocks of northeastern Utah, in Guidebook to the
 875 geology of the Uinta basin, Utah Geological Association, 8th Annual Field Conference Guidebook, p. 56-
 876 77

877 Sando, W.J., 1972, Madison Group (Mississippian) and Amsden Formation (Mississippian and
 878 Pennsylvanian) in the Beartooth Mountains, northern Wyoming and southern Montana, Montana
 879 Geological Society 21st Annual Field Conference Guidebook, p. 57-63

880 Sando, W.J., 1988, Madison Limestone (Mississippian) paleokarst: a geological synthesis, in: James,
 881 N.P., Choquette, P.W. (Eds.), *Paleokarst*, Springer-Verlag, New York, pp. 256–277.

882 Sando, W.J., Mackenzie, G.Jr., and Dutro, J.T.Jr., 1975, Stratigraphy and geologic history of the Amsden
 883 Formation (Mississippian and Pennsylvanian) of Wyoming, Geological Survey professional paper 848-A

884 Saperstone, H.I., and Ethridge, F.G., 1984, Origin and paleotectonic setting of the Pennsylvanian Quadrant
885 Sandstone, southwestern Montana, in Goolsby, J., and Morton, D., eds., The Permian and Pennsylvanian
886 Geology of Wyoming: Wyoming Geological Association 35th Annual Field Conference Guidebook, p.
887 309-331.

888 Schieber, J., 1999, Microbial mats in terrigenous clastics; the challenge of identification in the rock
889 record, *Palaios*, 14(1), 3-12. doi: 10.2307/3515357

890 Shebl, M.A., 1995, The impact of reservoir heterogeneity on fluid flow in the Tensleep Sandstone of the
891 Bighorn Basin, Wyoming Geological Association 35th Annual Field Conference Guidebook, p. 343-359.

892 Shepard, W., 1993, Upper Mississippian biostratigraphy and lithostratigraphy of central Montana, in:
893 Hunter, L.D., ed., Energy and mineral resources of central Montana: Montana Geological Society, p. 27-
894 36.

895 Siehl, A., and Thein, J., 1989, Minette-type ironstones, in: Young, T.P., and Taylor, W.E.G., eds.,
896 Phanerozoic Ironstones, Geological Society of London, Special Publications, 46(1), 175-193.

897 Sloss, L.L., 1950, Paleozoic sedimentation in Montana area, American Association of Petroleum
898 Geologists Bulletin, 34(3), 423-451,

899 Smith, L.B., and Read, J.F., 2000, Rapid onset of late Paleozoic glaciation on Gondwana: evidence from
900 upper Mississippian strata of the midcontinent, United States, *Geology*, v. 28, p. 279-282, doi:
901 10.1130/0091-7613(2000)28<279:ROOLPG>2.0.CO;2

902 Soil Survey Staff, 1999, Soil taxonomy: a basic system of soil classification for making and interpreting
903 soil surveys, U.S. Department of Agriculture, Natural Resources Conservation Service, Agriculture
904 Handbook 436

905 Sonnenfeld, M.D., 1996, Sequence evolution and hierarchy within the lower Mississippian Madison
906 Limestone of Wyoming, in Longman, M.W., Sonnenfeld, M.D. (Eds.), *Paleozoic Systems of the Rocky*

907 Mountain Region, Society for Economic Paleontologists and Mineralogists Rocky Mountain Section, pp.
908 165–192.

909 Steidtmann, J.R., 1974, Evidence for eolian origin of cross-stratification in sandstone of the Casper
910 Formation, southernmost Laramie Basin, Wyoming, Geological Society of America Bulletin, 85(12),
911 1835-1842. doi: 10.1130/0016-7606(1974)85<1835:EFEOOC>2.0.CO;2

912 Sweet, D.E., and Soreghan, G.S., 2010, Late Paleozoic tectonics and paleogeography of the ancestral
913 Front Range: Structural, stratigraphic, and sedimentologic evidence from the Fountain Formation
914 (Manitou Springs, Colorado), Geological Society of America Bulletin, 122(3-4), 575-594, doi:
915 10.1130/B26554.1

916 Tabor, N.J., and Poulsen, C.J., 2008, Palaeoclimate across the Late Pennsylvanian–Early Permian tropical
917 palaeolatitudes: a review of climate indicators, their distribution, and relation to palaeophysiographic
918 climate factors, Palaeogeography, Palaeoclimatology, Palaeoecology, 268 (3), 293-310, doi:
919 10.1016/j.palaeo.2008.03.052

920 Tabor, N.J., Montañez, I.P., Scotese, C.R., Poulsen, C.J., and Mack, G.H., 2008, Paleosol archives of
921 environmental and climatic history in paleotropical western Pangea during the latest Pennsylvanian
922 through Early Permian, Geological Society of America Special Papers, 441, 291-303. doi:
923 10.1130/2008.2441(20)

924 Tandon, S.K., and Gibling, M.R., 1994, Calcrete and coal in late Carboniferous cyclothems of Nova
925 Scotia, Canada: Climate and sea-level changes linked, Geology, 22 (8), 755-758. doi: doi: 10.1130/0091-
926 7613(1994)022<0755:CACILC>2.3.CO;2

927 Tenney, C.S., 1966, Pennsylvanian and Lower Permian deposition in Wyoming and adjacent areas,
928 American Association of Petroleum Geologists Bulletin, 50(2), 227-250.

929 Thompson, M.L., and Scott, H.W., 1941, Fusulinids from the type section of the Lower Pennsylvanian
930 Quadrant Formation, *Journal of Paleontology*, 15, 349-353.

931 Tidwell, W.D., 1967, Flora of the Manning Canyon Shale, Pt. I, a lowermost Pennsylvanian flora from
932 the Manning Canyon Shale, Utah and its stratigraphic sequence, *Brigham Young University Geology*
933 *Studies*, 14, 1-66.

934 Todd, L.M., 1996, Stratigraphy at the Boundary of the Tensleep Sandstone and Park City/Goose Egg
935 Formations in the Southern Big Horn Mountains and Eastern Owl Creek Mountains, Wyoming, Wyoming
936 Geological Association, 47th Annual Field Conference Guidebook, p.159-178,

937 Todd, T.W., 1964, Petrology of Pennsylvanian rocks, Bighorn Basin, Wyoming, *American Association of*
938 *Petroleum Geologists Bulletin*, 48(7), p.1063-1090,

939 Verville, G.J., 1957, Wolfcampian fusulinids from the Tensleep Sandstone in the Big Horn Mountains,
940 Wyoming, *Journal of Paleontology*, v. 31, p. 349-352,

941 Verville, G.J., and Thompson, E.E., 1963, Desmoinesian Fusulinids from the Minnelusa Formation in the
942 Southern Black Hills, South Dakota, Wyoming Geological Association/Billings Geological Society
943 Guidebook, Eighteenth Annual Field Conference, p. 61-66.

944 Verville, G.J., Sanderson, G.A., Brenckle, P.L., and Lane, H.R., 1973, Upper Paleozoic biozonation in the
945 Unit No. 19 well, Church Buttes Field, Uinta County, Wyoming. Wyoming Geological Association
946 Guidebook, Twenty-fifth Annual Field Conference, p. 165-171.

947 Verville, G.J., Sanderson, G.A., and Rea, B.D., 1970, Missourian fusulinids from the Tensleep Sandstone,
948 Bighorn Mountains, Wyoming, *Journal of Paleontology*, 38, 510-515.

949 Veevers, J.J. and Powell, C.McA., 1987, Late Paleozoic glacial episodes in Gondwanaland reflected in
950 transgressive–regressive depositional sequences in Euramerica, *Geological Society of America Bulletin*,
951 98, p. 475–487, doi: 10.1130/0016-7606

- 952 Wardlaw, B.R., and Collinson, J.W., 1986, Paleontology and deposition of the Phosphoria Formation:
 953 Contributions to Geology, University of Wyoming, v. 24, p. 107–142.
- 954 Wells, A.J., 1962, Recent dolomite in the Persian Gulf, *Nature*, 194, 274-275. doi: 10.1038/194274a0
- 955 West, I.M., Ali, Y.A., and Hilmy, M.E., 1979, Primary gypsum nodules in a modern sabkha on the
 956 Mediterranean coast of Egypt, *Geology*, 7(7), 354-358, doi: 10.1130/0091-7613(1979)7<354:PGNIAM>
 957 2.0.CO;2
- 958 Willis, R.P., 1959, Upper Mississippian-lower Pennsylvanian stratigraphy of central Montana and
 959 Williston basin, *American Association of Petroleum Geologists Bulletin*, 43(8), 1940-1966,
- 960 Wilson, P.C., 1962, Pennsylvanian stratigraphy of the Powder River Basin, in Branson, C.C., (ed.),
 961 Pennsylvanian System in the United States, *American Association of Petroleum Geologists*, 117-158
- 962 Wright, V.P., and Vanstone, S.D., 2001, Onset of late Palaeozoic glacio-eustasy and the evolving climates
 963 of low latitude areas: a synthesis of current understanding, *Geological Society of London, Journal*, v. 158,
 964 p. 579–582, doi: 10.1144/jgs.158.4.579
- 965 Ziegler, A.M., Rees, P.M., and Naugolnykh, S.V., 2002, The Early Permian floras of Prince Edward
 966 Island, Canada: differentiating global from local effects of climate change, *Canadian Journal of Earth
 967 Sciences*, 39(2), 223-238.

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- 971 Fig. 1: Palaeogeographic context of the western margin of the United States from the middle
 972 Mississippian to middle Pennsylvanian (Mississippian structures adapted from Maughan (1984);
 973 Pennsylvanian structures adapted from Huffman (2003)); PU = Pathfinder Uplift; CA = Chadron Arch.

974

975 Fig. 2: Time-space framework for the Carboniferous to Permian formations mentioned in this study, and
976 biostratigraphic data available in the literature. Time scale and ages from Gradstein et al. (2012). Age of
977 Madison Group according to Sonnenfeld (1996) and Katz et al. (2007). Arkosic, conglomeratic
978 formations surrounding the Ancestral Rocky Mountain uplifts, interpreted as alluvial fans shed from the
979 highlands, are not included in this synthesis. D. Sst. Mbr. = Darwin Sandstone Member; H. Sh. Mbr. =
980 Horseshoe Shale Member; R. Lm. Mbr. = Ranchester Limestone Member.

981

982 Fig. 3: Location of late Paleozoic formations in north-central Wyoming and south-central Montana
983 (redrawn from Love and Christiansen, 1985), and locations investigated during this study. AF = Alkali
984 Flats; BC = Bear Canyon; BI = Barry's Island; CC = Cottonwood Canyon; DA = Dayton; ML = Dry
985 Medicine Lodge Creek; SC = Shell Canyon; SM = Sheep Mountain; TC = Tensleep Canyon; TR =
986 Trapper Creek Canyon; WC = White Creek Canyon; ZC = Zeisman Canyon.

987

988 Fig. 4: (A) Outcrop expression of the Darwin Sandstone Member at Tensleep Canyon (Fig. 3); (B)
989 Tracing of the outcrop highlighting bounding surfaces (in bold) and dominant sedimentary structures; (C)
990 Palaeoflow directions gathered from trough cross-bedding on this exposure.

991

992 Fig. 5: (A) Outcrop expression of the interbedded red siltstones and pisolitic ironstone layers in the
993 Horseshoe Shale Member of the Amsden Formation at Tensleep Canyon (Fig. 3); (B) Close-up view of
994 one of the pisolitic ironstone layers. Red to brown-colored clasts are hematitic clasts, yellow-colored
995 clasts are iron pisoids; (C) Thin section of the same lithology; (D) Photomicrograph of an iron pisoid,
996 with alternating yellow and dark crinkly laminae.

997

Fig. 6: (A) Flat-stratified interval overlaid by a large cross-bedded set, respectively interpreted to represent the migration of wind ripples in a sand sheet environment and of large eolian dunes (upper Tensleep Formation at Dry Medicine Lodge Creek, Fig. 3); (B) Chert nodule with knobby, cauliflower-like surface; (C) Photomicrograph of length-slow chalcedony, exhibiting higher birefringence colors in the SW and NE quadrants following the insertion of a gypsum plate from the SE quadrant; (D) Surface rich in desiccation-cracks exposed under an overhang (Tensleep Formation at Shell Canyon, Fig. 3); (E) Two horizons of dolomicrite exhibiting knobby (bottom right) and prismatic (top left) ped structures (Ranchester Limestone Member at Dayton, Fig. 3).

Fig. 7: Distribution of climate-sensitive lithologies documented in this study and other indicators described by Todd (1966). Graphic log of a representative section, measured at White Creek Canyon (Fig. 3)

Fig. 8: Time-space framework for the Carboniferous to Permian formations mentioned in this study and the distribution of main lithological units. Lithologies obtained from Perry and Sloss (1943), Mundt (1956), Maughan and Roberts (1967), Maughan (1984), and Saperstone and Ethridge (1984) for Montana; Agatston (1954), Tenney (1963), Todd (1964), Steidtmann (1974), Fryberger (1984), Kerr and Dott (1988), Todd (1996), and Ahlbrandt et al. (2003) for Wyoming; Sadlick (1955, 1957), Prince (1963), Bissell (1964), and Driese and Dott (1984) for Utah and Colorado. See Fig. 2 for details on biostratigraphic data.

Fig. 9: Schematic representations of two models used to correlate formations across the Big Snowy Trough, the Wyoming Shelf, and the Doughnut Trough. (A) In this interpretation, the Horseshoe Shale Member is a lateral equivalent to the dark to gray shales of the Big Snowy Group and Manning Canyon

Formation. (B) In this interpretation, the Big Snowy Group and Manning Canyon Formation do not have equivalents on the Wyoming Shelf. The Horseshoe Shale Member corresponds to the Cameron Creek Member in Montana and the Molas Formation in Colorado.

Fig. 10: Palaeogeographic reconstructions for 3 Carboniferous time slices (Visean, Bashkirian, and Moscovian). Maps were generated using GPlates 1.3 software and plates reconstruction data of Domeier and Torsvik (2014b). Red dot denotes the location of study area (Bighorn Basin). The overall trend over this 30 Myr-long period consist of a northeastward drift, bringing the Bighorn Basin within 3° of the equator, followed by a more pronounced northward drift during the first half of the Pennsylvanian.

Fig. 11: From left to right: (1) Ages and stratigraphy (see Fig. 8 for legend) of the Carboniferous formations of Northern Wyoming; (2) Summary of the interpreted temporal evolution of climate from the early Visean to late Moscovian in this region based on these formations and contemporaneous ones in surrounding states; (3) Palaeolatitudes of the Bighorn Basin over time, estimated from Domeier and Torsvik's (2014b) reconstructions; (4) Temporal distribution of glacial deposits in Northwestern Argentina (Gulbranson et al., 2010), Eastern Australia (Fielding et al., 2008b), and Siberia (Raymond and Metz, 2004).

Fig. 12: (A) Palaeogeographic configuration of Pangaea during the Moscovian (middle Pennsylvanian) (Domeier and Torsvik, 2014b). Red arrows indicates motion of continents (Domeier and Torsvik, 2014a). Red dots denote the location of basins mentioned on the right; (B) Temporal evolution of climate in three basins across northern America. A = Arid; Sa = Semi-arid; Sh = Subhumid; H = Humid. Red curves indicate arid conditions, green curves represent humid settings, and dashed green and red curves indicate semi-arid to subhumid conditions.

Figure1_B&W

Figure 1

Figure2_B&W

Figure2

Figure3_B&W

Figure3

Figure4_B&W

Figure4

Figure5_B&W

Figure 5

Figure6_B&W

Figure6

Figure7_B&W

White Creek Canyon

44°32'56.76"N
107°42'28.04"W

Figure7

Figure8_B&W

Figure8

Figure9_B&W

Figure9

Figure10_B&W

Figure10

Figure11_B&W

Figure11

Figure12_B&W

Figure12