Development of longitudinal dunes under Pangaean atmospheric circulation

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Abstract. As a result of the large difference in heat capacity between land and ocean, global climate and atmospheric circulation patterns over~~in~~ the supercontinent Pangaea were significantly different from those of today. Modelling experiments indicate a seasonal alternation in cross-equatorial flow induced by the seasonal reversal in the direction of the monsoonal circulation~~have suggested the seasonal overturning of cross-equatorial Hadley circulation~~; however, there are large discrepancies between model-generated surface wind patterns and the reported palaeo-wind directions from aeolian dune records. Here, we present the ~~results of measurements of~~ spatial distribution of dune slip-face azimuths recorded in the Lower Jurassic aeolian sandstones over a wide area of the western United States (palaeolatitude: ~19°–27°N). The azimuth data of dune slip-faces reveal a bi-directional and oblique angular pattern that resembles the internal structures of modern longitudinal dunes. Based on the spatial pattern of slip-face directions and outcrop evidence~~s~~, we suggest that most of Lower Jurassic aeolian sandstones to be NNE–SSW- to NNW–SSE- oriented longitudinal dunes, which likely formed as the result of a combination of westerly, northwesterly, and northeasterly palaeo-winds. The reconstructed palaeo-wind pattern at ~19°–27°N appears to be consistent with the model-generated surface wind pattern and its seasonal alternation~~turnover~~. The reconstructed palaeo-wind patterns also suggest an influence of orbitally induced changes in atmospheric pressure patterns over~~configuration in~~ Pangaea.

1 Introduction

From the Carboniferous to the Jurassic, the supercontinent Pangaea dominated Earth. Because Pangaea was the largest pole-to-pole landmass in Earth's history, atmospheric circulation during this period is thought to have differed substantially from that of today (Kutzbach and Gallimore, 1989; Parrish, 1993). Modelling experiments have indicated that Pangaean atmospheric circulation was characteriz~~s~~ed by cross-equatorial wind flow induced by strong monsoonal circulation~~cross-equatorial Hadley circulation~~ and large seasonal movement of the intertropical convergence zone (ITCZ) to near 30° on land in both hemispheres (Kutzbach and Gallimore, 1989; Parrish, 1993; Rowe et al., 2007). Some studies have also suggested significant changes in atmospheric pressure patterns ~~in~~ over Pangaea caused by orbital-scale changes in the seasonal and latitudinal distribution of solar radiation (Kutzbach, 1994; Winguth and Winguth, 2013). However, the terrestrial environmental response to such seasonal- and orbital-scale changes in atmospheric pressure patterns during this period remains poorly known~~largely uncertain~~.

The aeolian dune record provides ~~significant~~ information ~~of surface~~on the prevailing surface wind regime and atmospheric circulation patterns in the past (Lancaster, 1981; Parrish and Peterson, 1988; Peterson, 1988; Livingstone, 1989; Lancaster, 1990; Kocurek, 1991; Scherer, 2000; Lancaster et al., 2002; Loope et al., 2004; Beveridge et al., 2006; Sridhar et al., 2006; Rodríguez-López et al., 2008; Hasegawa et al., 2012). Modern deserts are ~~generally~~ mostly developed in the subtropical high-pressure belt as a result of downwelling of the Hadley circulation, except for the interiors of Eurasia and North America where a continental climate and monsoonal circulation are predominant. ~~and a~~Aeolian dunes in desert areas record the prevailing surface wind pattern (e.g., trade winds and westerlies) in the form of large-scale cross-beds (Breed et al., 1979; Lancaster, 1981; Wasson et al., 1988; Hesse, 2010; Hasegawa et al., 2012). In addition, ~~the~~ patterns of dune alignment and morphology have been considered to reflect the prevailing wind regime and mesoscale circulation patterns along with ~~its~~ seasonal and long-term variations in wind direction (Bristow et al., 2000; Beveridge et al., 2006; Sridhar et al., 2006; Bristow et al., 2007; Zhou et al., 2012; Telfer and Hesse, 2013; Liu and Baas, 2020), although dune morphology also depends on sediment availability, erodibility, and vegetation cover~~s~~ (du Pont et al., 2014; Gao et al., 2015). The spatial distribution of palaeo-wind patterns inferred from~~recorded in~~ aeolian dune slip-face azimuths thus allows the deduction of atmospheric circulation patterns in geological periods characteriz~~s~~ed by different land–sea distributions (Parrish and Peterson, 1988; Peterson, 1988; Scherer, 2000; Loope et al., 2004) or different palaeoclimatic settings (Beveridge et al., 2006; Sridhar et al., 2006; Rodríguez-López et al., 2008; Hasegawa et al., 2012).

Peterson (1988) initially described the spatial and temporal changes in palaeo-wind regimes from Carboniferous to Middle Jurassic aeolian sandstone in the western United States (US) (i.e., the Colorado Plateau and surrounding area). Using these datasets and published palaeomagnetic data, Loope et al. (2004) suggested the predominance of a desert environment in the Pangaean equatorial area (palaeolatitude 8°–13°N), with a broad sweep of SW-ward winds in the northern area changing~~curving~~ to SE-ward winds in the southern area during the Early Jurassic. However, the reconstructed surface wind pattern shows discrepancies with the results of model-based reconstructions (Rowe et al., 2007), even though the revised palaeolatitude of the Colorado Plateau (17°–24°N) has been used. Rowe et al. (2007) suggested several possible reasons for this discrepancy, including (1) the palaeomagnetism-based palaeogeographic reconstructions of the Jurassic are incorrect, (2) the interpretation of how winds shaped the dunes is mistaken, or (3) the basic climate controls during the Jurassic were different from those of today.

We considered the problems involved in the measurement of palaeo-wind direction data from the aeolian dune record. Peterson (1988) provided only single preferred palaeo-wind directions at each site without information on dune morphology, thus hindering the understanding of accurate palaeo-wind flow regimes. Threfore, r~~R~~e-evaluation of palaeo-wind direction data with a particular focus on dune morphology and a multi-directional wind regime therefore could provide an explanation forexplain the discrepancy between reconstructed surface wind patterns and model-based reconstructions. In addition, recent palaeomagnetic studies that addressed the inclination-shallowing problem (Kent and Irving, 2010; Dickinson, 2018) provide the revised palaeolatitude of the Colorado Plateau as N19°–27° during the Early Jurassic, which corresponds to the location of the model-generated desert area and the subtropical high-pressure belt (Rowe et al., 2007). To solve the discrepancies between model experiments and wind patterns inferredthe reconstruction from -from aeolian dune records, re-evaluation of the Lower Jurassic aeolian dune slip-face azimuth record, considering the latest palaeogeographical reconstruction is required.

Here, we present the measurement results of spatial distribution of slip-face azimuths and inferred dune morphology recorded in Lower Jurassic aeolian sandstones in the western US, together with the latest palaeolatitude data (Kent and Irving, 2010; Dickinson, 2018). Our measurement of slip-face orientations over a wide area of the western US and field observational evidence reveals that the presence of longitudinal dunes in the Early Jurassic desert that formed as a result of tri-directional palaeo-wind patterns, consistent with model-generated seasonal wind regimes (Rowe et al., 2007). We also discuss the formation process of longitudinal dunes in possible relation to orbitally induced changes in the atmospheric pressure configurationpattern, by comparing the inferred wind patterns with climate model reconstruction for the Pangaea supercontinentclimate model reconstruction in Pangaea supercontinent (Winguth and Winguth, 2013) and geological evidence for late Quaternary dune alignments (Lancaster, 1981; Lancaster, 1990; Bristow et al., 2000; Lancaster et al., 2002; Bristow et al., 2007).

2 Material and Methods

2.1 Lower Jurassic aeolian sandstone

To obtain the spatial distributions of palaeo-wind directions, we surveyed Lower Jurassic aeolian sandstone strata and measured aeolian dunethe maximum slip-face azimuths of the dunes over a wide area, in the western US,; specifically, the Navajo Sandstone on the Colorado Plateau (Utah, Colorado, and Arizona) and correlative strata of the Nugget Sandstone to the north (Idaho, Wyoming) and the Aztec Sandstone to the south (Nevada) (**Fig. 1**). The maximum thickness of the strata is approximately ~700 m, in southern-central Utah, and thin to approximatelythinning to ~100–150 m toward in the northern area (Nugget Sandstone in Idaho and Wyoming) and eastern area (Glen Canyon Sandstone in western Utah and Colorado) (Blakey et al., 1988; Parrish and Peterson, 1988; Peterson, 1988; Blakey, 2008). The estimated size of theThis palaeo-dune field covers a vast area of approximatelyis ~625,000 km^2, an areawhich is 2.5 times larger than the size of the remaining outcropsurface and subsurface extent of the strata (Marzolf, 1988; Kocurek, 2003; Tape, 2005). On the basis of existing palaeomagnetic studies (Kent and Irving, 2010; Dickinson, 2018), the palaeolatitude of the studied palaeo-dune field is inferred to have been ca. 19°–27°N during the Early Jurassic, with clockwise continental rotation of the continent by ~5°.

The c~~C~~hronology and correlation of the Lower Jurassic aeolian sandstone (Navajo Sandstone and correlative strata) in western US ~~is currently~~are debated (Dickinson and Gehrels, 2009; Dickinson et al., 2010; Sprinkel et al., 2011; Rowland and Mercadante, 2014; Parrish et al., 2019). Based on the U–Pb age dating of detrital zircons, the depositional ages of the underlying Kayenta Formation and~~ the~~ overlying Page Sandstone are considered to be 190–187 Ma and 170 ±3 Ma, respectively (Dickinson and Gehrels, 2009). From the U-Pb and $^{40}Ar/^{39}Ar$ ~~geochronology for~~ages of ~~-~~pyroclastic zircon and biotite crystals from tephra lenses in the basal part of the Page Sandstone ~~further provide the~~yield an upper age limit ~~age of~~for the Navajo Sandstone as 172.3–170.6 Ma (Dickinson et al., 2010). Based on these existing ages, ~~chronological data sets,~~ the duration for deposition of the Lower Jurassic aeolian sandstone is estimated ~~as~~ to be ca. 14.7–19.4 Myr. On the other hand, Parrish et al. (2019) ~~recently~~ proposed ~~significantly~~ a much older age (200.5 ±1.5 Ma and 195.0 ±7.7 M) for the Navajo Sandstones in southeastern Utah based on ~~the~~ U-Pb analyses of carbonate deposits. These ages~~This new chronological data~~ suggest~~s~~ that the basal part of the Navajo Sandstone and the underlying Kayenta Formation are interfingered~~ing~~ ~~and/~~or even time-transgressive over a ~~few~~ period of serveral million years (Parrish et al., 2019).

Stratigraphic correlation of cross-strata in the Lower Jurassic aeolian sandstone over a wide area of western US is challenging due to the chronological problems described above and a lack of first-order bounding surfaces with wide extent~~lack of comparable first-order bounding surfaces~~. Although it is difficult to accurately correlate the strata ~~in each~~among regions, we investigated the palaeo-wind records over a wide area~~ in order~~ to obtain the spatial distribution ~~pattern~~ of palaeo-wind directions as shown in **Fig. 1**. The ~~obtained~~ results may not represent a truly contemporaneous data~~-~~sets at different sites, and determining the exact spatial distribution ~~pattern in the same~~for a given time-window needs further chronological research. Nevertheless, we believe that the spatial distribution of palaeo-wind directions presented in this study is important because it represents an integrated pattern of mesoscale wind regimes in the western US area of the Pangaea supercontinent during the Early Jurassic.

2.2 Reconstruction of spatial palaeo-wind patterns

Palaeo-wind directions at each sites were determined based on ~~the~~ measurements of the maximum slip-face dip azimuths at each outcrop~~s~~ of cross-bedding strata. In total, w~~W~~e measured ~~totally~~ 1636 slip-face azimuths ~~data~~ from 178 sites (**Supplementary table**). Unlike~~ the~~ Peterson (1988), who reported~~which demonstrated~~ only single preferred palaeo-wind directions at each site, we provided the multi-directional palaeo-wind regime as rose diagrams shown in **Fig. 1**. We also show~~ed~~ regional-scale slip-face azimuth data and outcrop evidence ~~of~~ for the Navajo Sandstone in Zion National Park (~~,~~ southwestern Utah)~~,~~ and Arches National Park (~~,~~ eastern Utah) (**Figs. 2, 3**). The ~~obtained~~ slip-face azimuth data were corrected for the magnetic declination (+11°) in the western US (Thébault et al., 2015) and bedding tilt~~s~~, using the Kyoto Untilting Tool software (Tomita and Yamaji, 2003) developed by the Yamaji Laboratory, Kyoto University. The obtained slip-face azimuth data were then corrected for post-Jurassic ~~continental~~ clockwise rotation of the continent (5°) and plotted on a palaeogeographic map (**Fig. 1**) with palaeolatitudes based on palaeomagnetic data (Dickinson, 2018; Kent and Irving, 2010). The ~~obtained~~

palaeo-wind data were plotted on rose diagrams using the analytical software "Rose" developed by the Naruse Laboratory, Kyoto University.

The obtained slip-face azimuth data commonly show~~s~~ multiple palaeo-wind direction~~–~~s in the rose diagrams~~patterns~~. To statistically separate multiple palaeo-wind directions and calculate the median directions~~components and calculate preferred median directions~~, we used a "Gaussian Mixture (GM) model" assuming that the data distribution reflects~~is generated from~~ a mixture of a finite number of Gaussian (Normal) distributions. Using an e~~E~~xpectation-maximization (EM) algorithm ~~fitting~~ to fit the GM model, we separated slip-face azimuth data into multiple components (distributions), and finally calculated the median palaeo-wind directions at each site. The numbers of c~~C~~omponent ~~numbers are estimated~~was determined either by cluster~~ing~~ analysis or from the number~~s~~ of major peaks in histograms of slip-face azimuth data at each site~~s~~ (**Table 1**).

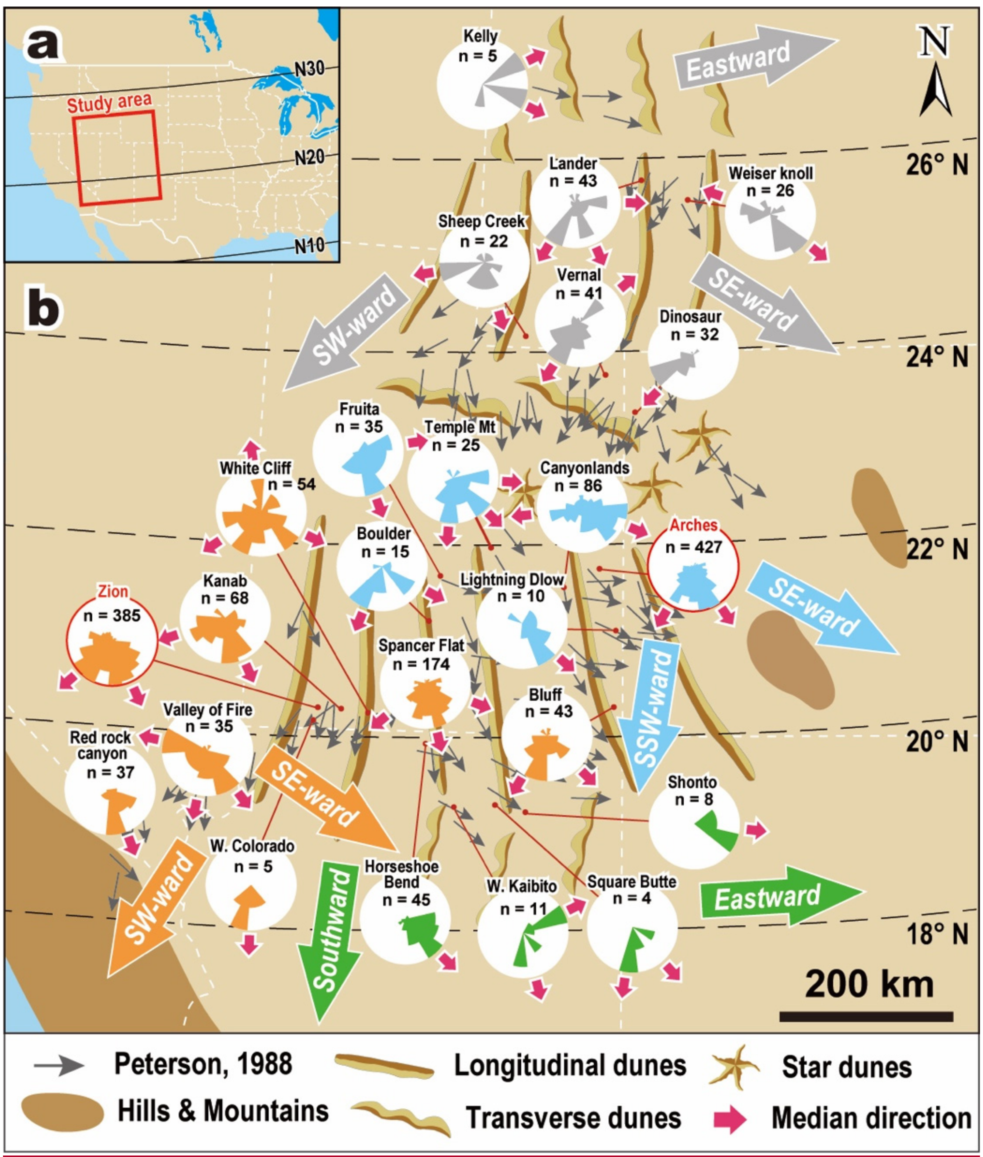

Figure 1: Reconstructed palaeo-wind patterns in the western US during the Early Jurassic. (a) Location of the study area in the western US. (b) Spatial distributions of dune slip-face azimuths measured in this study (shown on rose diagrams) and inferred dune morphologies, plotted on the Early Jurassic palaeogeographic map of Peterson (1988) with palaeolatitudes based on Dickinson (2018). The colours of the r~~R~~ose diagrams indicate the~~in each~~ area~~s are shown by different colour~~: northern (grey), central (light blue), southwestern (orange), and southern (green) parts of the study area. Large~~-size~~ arrows ~~shown~~ in (b) indicate the reconstructed prevailing surface wind directions in each area. The pink ~~coloured~~ arrows around the outside of~~in~~ each rose diagrams indicate the median direction~~s~~ of separated components in the slip-face azimuth data ~~shown~~ provided in Table 1.

Table 1: **Calculated median directions of slip-face azimuths ~~in~~ at each sites. Original data are provided~~is shown~~ in Supplementary Table~~ 1~~.**

Study sites	Number of data	Median direction 1	Median direction 2	Median direction 3	Study sites	Number of data	Median direction 1	Median direction 2	Median direction 3
Kelly*	5	63.5°	116.0°	–	Zion	385	156.3°	228.3°	–
Lander*	43	91.0°	156.0°	212.0°	Kanab	68	156.4°	252.1°	–
Weiser knoll	26	129.7°	290.5°	–	White Cliff	54	116.2°	236.2°	351.7°
Sheep Creek	22	163.8°	260.6°	–	Spencer Flat	174	111.3°	166.6°	230.4°
Vernal	41	49.7	212.7°	–	Bluff*	43	135.5°	211.0°	–
Dinosaur	32	223.9°	–	–	Red rock canyon	37	159.3°	–	–
Fruita	35	81.5°	159.4°	–	Valley of Fire	35	143.3°	192.0°	282.8°
Temple Mountain*	25	94.0°	135.0°	185.0°	Western Colorado	5	182.0°	–	–
Canyonlands	86	112.3°	264.0°	–	Horseshoe Bend	45	134.6°	–	–
Arches*	427	146.0°	211.0°	–	Western Kaibito	11	64.0°	165.2°	–
Lightning Dlow	10	132.0°	–	–	Square Butte	4	137.6°	188.5°	–
Boulder	15	118.3°	202.8°	–	Shonto	8	96.0°	–	–

*Separation of components and median directions ~~in~~ at these sites are ~~calculated~~ based on histogram~~s~~ of slip-face azimuth~~data~~ distribution.

3 Results and Discussion

3.1 Development of NNE–SSW- to NNW–SSE-oriented longitudinal dunes

The spatial distribution of dune slip-face azimuths obtained in this study indicates multiple directions of palaeo-wind flow, ~~with overall tri-modal preferred directions of~~ mainly eastward, southeastward, and southwestward (**Fig. 1b**). Although ~~a previous study (~~Peterson~~,~~ (1988) ~~demonstrated~~ reported a single preferred palaeo-wind direction for each region, which is overall consistent with our data, the obtained datasets show ~~marked~~ multiple direction~~al patterns~~s. In addition, the slip-face azimuths in most of the regions show bi-directional and oblique angular variation between ~80° and 135°.

Outcrop evidence of slip-face azimuth data~~s~~ of the Navajo Sandstone in Zion National Park and Arches National Park are illustrated in **Figs. 2 and 3**, respectively. The rose diagrams for the Zion region show bi-modal preferred directions ~~to~~ toward the SSE and SW (centred at ~160° and ~240°). In addition, the preferred direction switches between SSE-wards and SW-wards at horizontal intervals of ~~approximately~~ ~1 km (**Fig. 2a**). The rose diagrams ~~for~~ of the Arches region also show bi-modal preferred directions to the SE and SSW (centred at ~140° and ~220°) and changes in~~with switching of~~ preferred directions at horizontal intervals of ~ ~~approximately~~ 1–2 km (**Fig. 3a**). In both regions, t~~T~~he outcrops located at the boundaries between areas~~, which is located in the boundary~~ of bi-directional and oblique angular slip-face directions~~,~~ show~~s~~ zigzagging patterns and compound sets of cross-stratification ~~in both regions~~ (**Figs. 2c, 3c**). The observed bi-directional cross-bed structures exhibit a marked correspondence ~~to~~ with the internal structures of modern longitudinal dunes as reconstructed ~~on the basis of~~from ground-penetrating radar (GPR) profiles (Bristow et al., 2000; Bristow et al., 2007; Zhou et al., 2012; Telfer and Hesse, 2013; Liu and Baas, 2020) (**Figs. 2e, 3e**~~**Appendix A**~~). Internally, modern longitudinal dunes exhibit oblique bi-directional cross-beds on each side of the dune flank and stacking of cross-beds in both directions in the central part. In the central part of longitudinal dunes, the vertical stacking of two oblique opposing-direction cross-sets result in increasing dune height and sets of trough cross-stratification (**Figs. 2e, 3e**). Optically stimulated luminescence (OSL)~~ age~~ dating has further constrained~~elucidated~~ the timing and duration of cross-beds and~~ the~~ wind regimes during the formation of cross-bedding (Bristow et al., 2000; Bristow et al., 2007; Zhou et al., 2012). Sets of trough cross-stratification are formed in the central dune crest by superposition of bi-modal dunes. These structural features are also observed in outcrops of Navajo Sandstone strata in the Zion and Arches regions (**Figs. 2c, 3c**), and are therefore interpreted to have been formed by the vertical stacking of cross-sets of longitudinal dunes. The change in preferred direction at horizontal intervals of 1–2 km~~1–2 km intervals~~ (**Figs. 2a, 3a**) is also consistent with the spacing of modern longitudinal dunes (Wasson and Hyde, 1983; Lancaster, 2006).

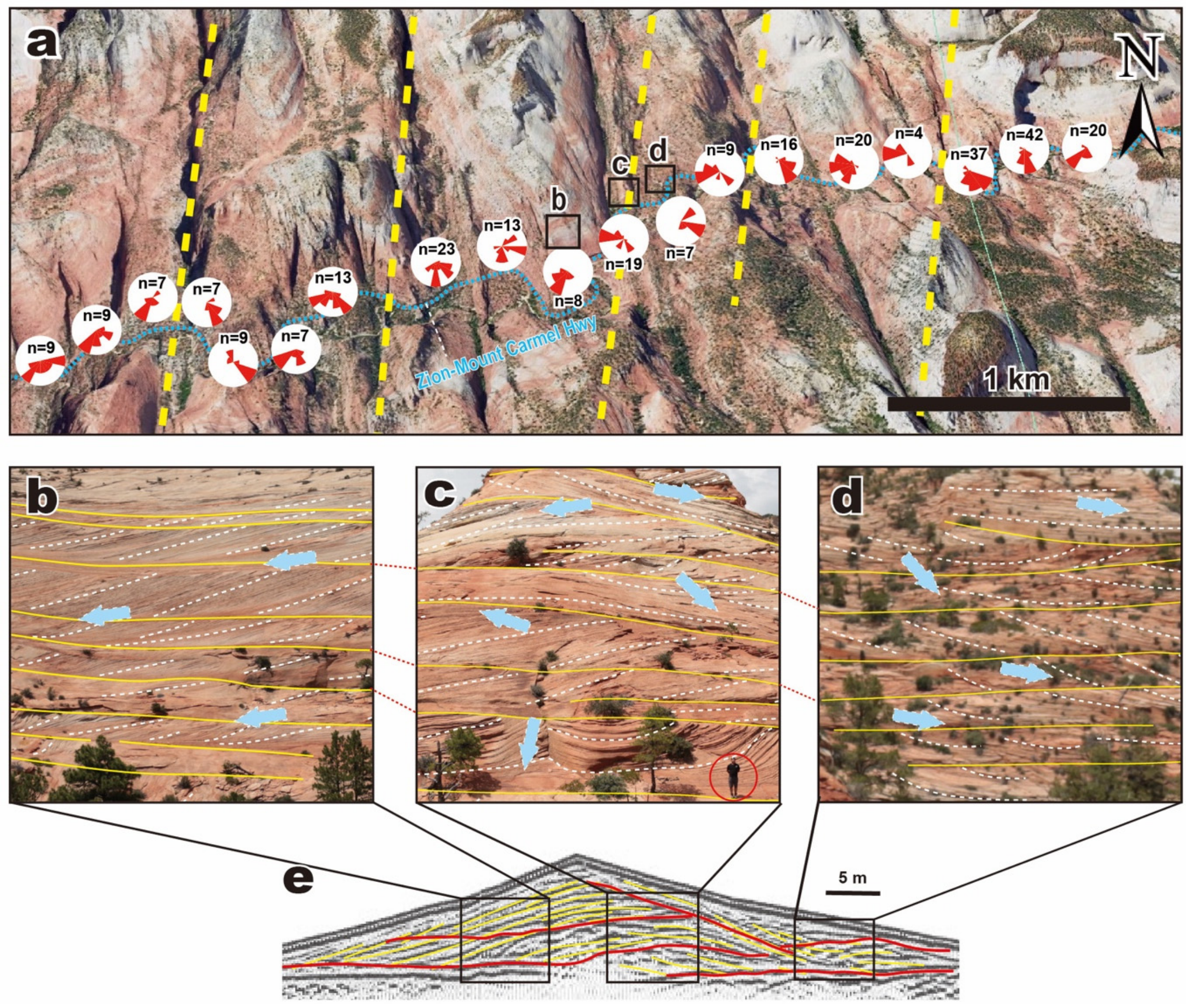

Figure 2: Spatial pattern of dune slip-face azimuths and outcrop photographs of the Navajo Sandstone in the Zion National Park, and comparison with the internal structure of a modern longitudinal dune.~~.~~ (a) Spatial distribution of palaeo-wind data ~~shown by rose diagrams~~ along the Zion–Mount Carmel Highway. Yellow dotted lines are the inferred locations of the central crests of longitudinal dunes, which are spaced at horizontal intervals of ~1 km intervals~~approximately 1 km intervals~~. (b–d) Outcrop photographs of cross-stratification ~~structures~~ in the Navajo Sandstone. Yellow solid lines and white dashed lines indicate the bounding surfaces of aeolian dune strata and slip-face cross-stratifications, respectively. All photographs were taken facing ~~to~~ north. Red circle in (c) indicates a person for scale (ca. 1.7 m tall). (e) Ground-penetrating radar (GPR) profiles showing the internal structure of a modern longitudinal dune (Bristow et al., 2000). Yellow and red traces indicate slip-faces and unconformities, respectively.

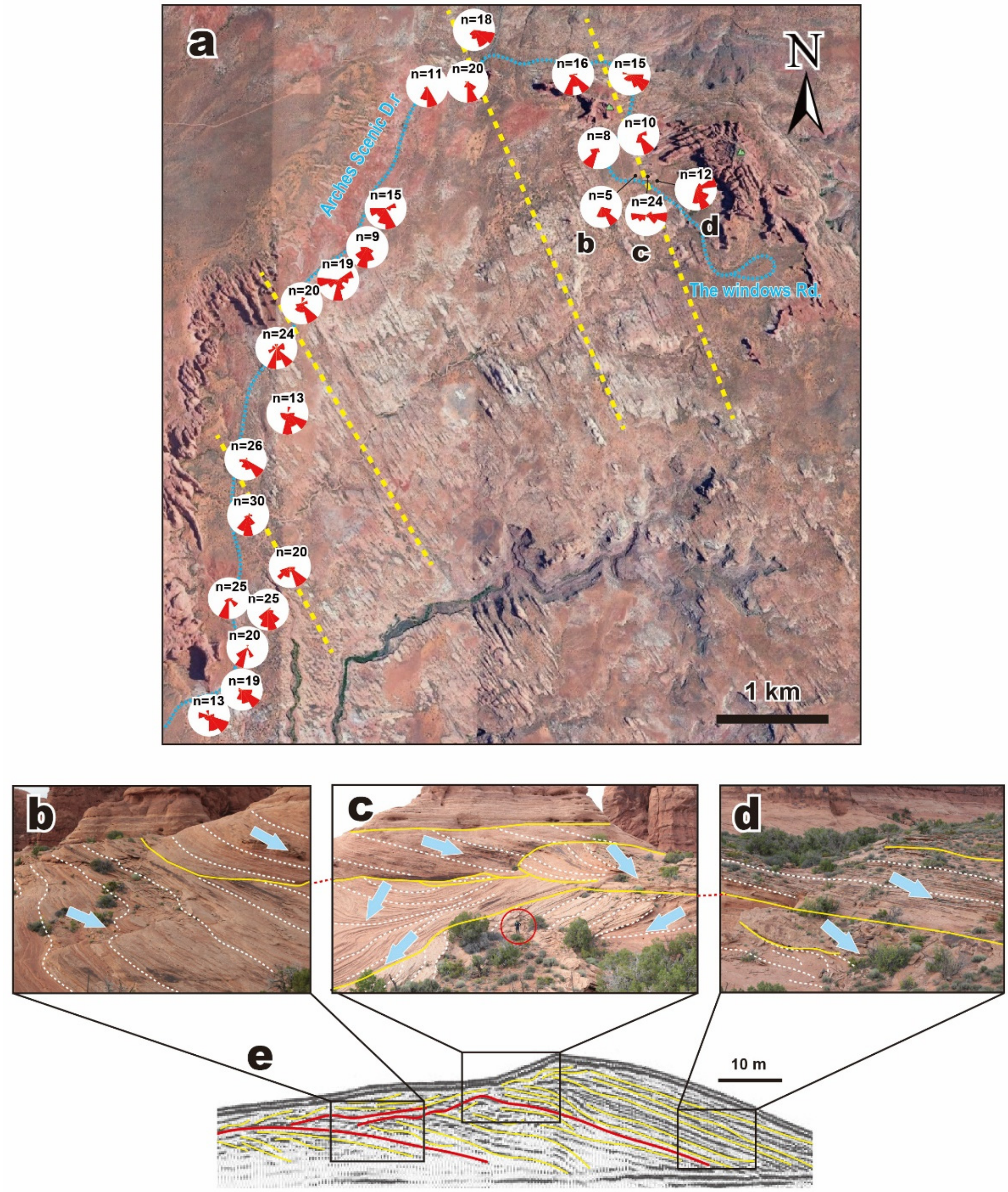

Figure 3: Spatial pattern of dune slip-face azimuths and outcrop photographs of the Navajo Sandstone in the Arches National Park, and comparison with the internal structure of a modern longitudinal dune.~~.~~ (a) Spatial distribution of palaeo-wind data ~~shown by rose diagrams~~ along the Arches Scenic Drive. Yellow dotted lines are the inferred locations of the central crests of longitudinal dunes. (b–d) Outcrop photographs of cross-stratification structures in the Navajo Sandstone. Yellow solid lines and white dashed lines indicate bounding surface and slip-face cross-stratification~~,~~s respectively. All photographs werw taken facing ~~to~~ north. Red circle in (c) indicates a person for scale (ca. 1.7 m tall). (e) Ground-penetrating radar (GPR) profile showing the internal structure of a modern longitudinal dune (Bristow et al., 2000). Yellow and red traces indicate slip-faces and unconformities, respectively.

The angles ~~of~~ between the observed bi-modal directions ~~in~~ of the slip-face azimuth ~~exhibits~~ are in good agreement with experimental estimates of the angles ~~of~~ between the flow directions ~~to~~ that form longitudinal dunes. Water flume experiments simulating the formation of different types of dune have suggested that longitudinal dunes form under bi-directional flows with angles of 90°–135° between flows, and lie along the average wind direction (Taniguchi et al., 2012). The formation of longitudinal dunes by seasonal alternationsturnover of oblique wind flow is also consistent with numerical modelling (Parteli et al., 2014; Gao et al., 2015; Liu and Baas, 2020) and observational studies (Breed et al., 1979; Wasson et al., 1988; Livingstone, 1989; Hesse, 2010; Zhou et al., 2012). It should be noted that longitudinal dunes are also formeds under uni-modal wind regimes by the influence of vegetation, clay and salt content, and related sediment cohesiveness, whilst sinuous uni-directional dunes are also forms under bi-modal wind regimes by the influence of sand availability (du Pont et al., 2014; Gao et al., 2015). However, the zigzagging patterns and compound sets of cross-stratification preserved in the Navajo Sandstone of in the Zion and Arches regions (**Figs. 2c, 3c**) resemble the features ofare resembling to inferred longitudinal dunes inof other aeolian dune strata (Scherer, 2000; Abrantes et al., 2020). In addition, GPR observation of modern sinuous uni-directional dunes (Fu et al., 2019) indicate bi-directional but relativelyrather thinner cross-bed structures compared with that those of longitudinal dunes (Bristow et al., 2000; Bristow et al.,2007; Zhou et al., 2012; Telfer and Hesse, 2013; Liu and Baas, 2020). Therefore, the Navajo Sandstone in the Zion and Arches regions are is interpreted to be formed by longitudinal dunes, consistent with earlier suggestion by Rubin and Hunter (1985).

In addition to these the outcrop evidence in the Zion and Arches regions, the spatial pattern of slip-face directions suggests that longitudinal dunes are were widely distributed in the western US that and were oriented NNW–SSE to NNE–SSW in the palaeolatitude range ~20°–26°N during the Early Jurassic (**Fig. 1b**). The obtained data further indicaterepresent the characteristic wind flow regimes in each of the four areas. Specifically, the slip-face azimuths in the southernmost area (palaeolatitude: ~19°N) show a bi-directional pattern of eastward and southward palaeo-winds, whereas the southwestern and southeastern areas (palaeolatitude: ~20°–22°N) show preferred SW-ward and SE-ward directions, with a strongeran increased influence of easterlywestward palaeo-winds in the southwestern area. The central area (palaeolatitude: ~22°N) shows more complex and multi-directional patterns, suggesting the presence of some star dunes (Lancaster, 1989). In contrast, the southern part of northern area (palaeolatitude: ~23°N) shows uni-directional preferred SW-ward directions suggesting the dominance of transverse dunes, which is also consistent with the evidence of NW–SE-oriented underground dune structures inferred fromtextures reconstructed by means of seismic inversion (Verma et al., 2018). The northern area (palaeolatitude: ~24°–26°N) shows a bi-directional palaeo-wind pattern of toward the SW-ward and SE-ward directions, whereas the northernmost area (palaeolatitude: ~27°N) shows a stronger influence of eastward palaeo-wind, although the possibility of sampling bias should be considered.more influence of eastward palaeo-wind flows.

3.2 Comparison of modelled and observed surface wind patternsOrbital-scale changes in Pangaean atmospheric pressure configuration

The observed tri-directional pattern of slip-face azimuths suggests that the longitudinal dunes were formed as the result of a combination of westerly, northwesterly, and northeasterly palaeo-winds (**Fig. 1b**). The reconstructed tri-modal palaeo-wind directions are consistent with the model-generated prevailing surface wind patterns, including northeasterly trade winds over the study area during the boreal winter, and northwesterly winds during the boreal summer (Rowe et al., 2007).

The reconstructed tri-modal palaeo-wind directions are also consistent with model results inferring seasonal- and orbital-scale changes in wind regime (Winguth and Winguth, 2013).~~Using observed multi-directional dune slip-face azimuth patterns (**Fig. 1b**), in conjunction with the model simulation result (Winguth and Winguth, 2013), we illustrated the inferred seasonal- and orbital-scale changes in wind regime and the resulting dune alignments for precession maximum and minimum (**Fig. 4**).~~ The main result of~~ principal difference resulting from~~ orbitally induced changes in the atmospheric pressure pattern~~configuration~~ is the predominance of a subtropical low-pressure system (continental) at ~20°–25°N in~~during~~ the boreal summer during the eccentricity-modulated precession maximum ~~at precession maximum~~ (Winguth and Winguth, 2013; **Fig.4c**). The resulting large subtropical low-pressure cell diverts the moist tropical air masses of the ITCZ away from Panthalassa and results in strong precipitation across subtropical Pangaea (Winguth and Winguth, 2013)~~(**Fig. 4c**)~~. In contrast, the development of the strong continental high-pressure system at ~30°N results in the dominance of dry NE trade winds over the study area during winter (Winguth and Winguth, 2013; **Fig. 4a**). The movement of dune sand was probably stabilized by i~~I~~ntense summer rainfall ~~in the southern area (~20°–22°N)~~ and resulting~~ed~~ higher groundwater table and enhanced vegetation ~~and soil covers likely stabilized dune-sand movement and resulted in enhanced sand accumulation~~ (Kocurek, 2003; Durán and Herrmann, 2006;~~Lancaster and Baas, 1998;~~ Hesse and Simpson, 2006~~; Kocurek and Ewing, 2012~~), which seems consistent with the development of bounding surfaces and evidence of trace fossils (invertebrate burrows) within dune slip-faces in south-central Utah~~the maximum thickness of the Navajo Sandstone in south-central Utah (Blakey et al., 1988; Parrish et al., 2019). Increased humidity and vegetation in the southern area is also consistent with the evidence of nodular layers and trace fossils within dune slip-faces in south-central Utah~~ (Chan and Archer, 2000; Loope and Rowe, 2003;~~Loope et al., 2001~~; Ekdale et al., 2007).

On the other hand, the development of a high-pressure system led to arid climatic conditions over the entire study area in both summer and winter during the eccentricity-modulated precession minimum (Winguth and Winguth, 2013; **Fig. 4b, d**). The boreal summer precipitation was reduced in subtropical Pangaea, and the strengthening of the high-pressure system over the Panthalassa resulted in dry NW and NNW winds (Winguth and Winguth, 2013). In addition, the continental high-pressure system (weaker than insolation maximum) resulted in dry NE trade winds during the boreal winter (Winguth and Winguth, 2013). ~~In the northern areas, relatively dry NNW winds prevailed during summer (**Fig. 4c**). In contrast, owing to the development of the high-pressure system at ~30°N, dry NE trade winds prevailed over study area during winter (**Fig. 4a**).~~ Because of this seasonal and orbital-scale wind regime alternation between the eccentricity-modulated precession maximum (winter: NE trade winds; summer: dune stabilization) and minimum (winter: NE trade winds; summer: NW and NNW winds)~~turnover of bi-modal winds~~, NNE–SSW- to NNW–SSE-oriented longitudinal dunes are inferred to have formed in the southern and central areas (~20°–25°N) ~~were developed during precession maximum~~ (**Fig.**

4~~**a, c**~~). ~~In contrast, owing to the development of a high-pressure system, arid climatic conditions prevailed in the whole study area in both summer and winter during precession minimum (Winguth and Winguth, 2013) (**Fig. 4b, d**). In the central and southern areas, winter NE trade winds and summer NNW to NW winds occurred; as a result, NNW–SSE-oriented longitudinal dunes were developed in these areas (~20°–22°N). In the northern area at around 23°N, star dunes likely formed as a result of multi-directional wind flows in the center of a high-pressure system in winter.~~ In the northernmost area (~27°N), westerly winds dominated in ~~both~~ summer during the eccentricity-modulated precession minimum~~and winter~~, forming~~so~~ eastward- migrating transverse dunes~~moving barchanoid dunes likely developed there during precession minimum~~ (**Fig. 4b**).

~~Observed bi-modal slip-face azimuth patterns and outcrop evidences also implies influence of orbital-scale changes in atmospheric pressure regimes. The vertical profile of inferred central crests of longitudinal dune strata in Zion and Arches shows trough-shaped cross-stratified structures with SW-ward and SE-ward slip-face azimuths (**Figs. 2c, 3c**). The inversion of this paleo-wind pattern appears to occur every ca. 2–3 m of stratigraphic thickness.~~ Previous studies also raised the possibility that orbital-scale climatic changes are recorded in aeolian depositional sequences in subtropical Pangaea, such as~~This interpretation is consistent with the evidence of~~ fluvial–aeolian ~~depositional~~ cycles (~20m thick) ~~of~~ in the Lower Jurassic Navajo–Kayenta transition in ~~Kanab,~~ Utah ~~(~20 m)~~ (Hassan et al., 2018), aeolian cyclic sequences (~4–8 m and ~18–22 m thick) in the Permian Cedar Mesa Sandstone in Utah (Mountney, 2006), and ~~Permian~~ aeolian–alluvial ~~depositional~~ cycles (~2–15 m thick) in the Permian Ingleside Formation in Colorado ~~(2–15 m cycles)~~ (Pike and Sweet, 2018), which are ~~both~~ interpreted to reflect the 100-kyr and 400-kyr eccentricity cycles. A previous study also suggested that the bioturbated zones and the bounding surfaces in the Navajo Sandstone likely reflected orbital-scale pluvial episodes (Loope & Rowe, 2003). Although the Navajo Sandstone in the Zion region does not contain well-defined facies cycles or well-developed palaeosols, the bounding surfaces appear to occur every ca. 2.9 ±0.9 m of stratigraphic thickness (**Fig. 2b–d**; **Supplementary Table**). ~~Based on the~~On the basis of existing chronological data (Dickinson and Gehrels, 2009; Dickinson et al., 2010~~; Parrish et al., 2019~~), we estimated~~assume~~ the duration of deposition of the ~~Lower Jurassic aeolian~~Navajo ~~sandstone~~ Sandstone to be ca. 14.7–19.4 Myr and its~~with a~~ thickness ~~of~~ to be 300–700 m; thus, the average accumulation rate ~~of the deposits~~ can be calculated ~~to be~~as ca. 1.5–4.8 cm/kyr. Based on this estimated accumulation rate, the bounding surface of dune strata (every ~2.9 m)~~paleo-wind inversion (every 2–3 m)~~ formed at intervals of~~occurred every~~ ~~42~~60–~~200~~ 193 kyr, which is in agreement with ~~of~~ the ~~orbital change~~ time-scale of the ~~(i.e., 20-kyr precession, 40-kyr obliquity and~~ 100-kyr eccentricity cycle~~s)~~, consistent with previous studies. ~~Although GPR observation and OSL dating of modern longitudinal dune formation (Bristow et al., 2000; Bristow et al., 2007) have revealed that the time-scale of dune cross-bed is slightly shorter (centennial- to millennial-scale), orbital-scale changes in the area of the dune formation field likely cause much a longer time-scale of vertical dune accumulation.~~

These lines of evidence, in conjunction with a comparison of observed palaeo-wind directions and model-generated wind patterns, indicate that orbital-scale climate change may have influenced the development of longitudinal dune-fields in Pangaea. Although preservation of the palaeoenvironmental record is generally hampered by the erosion of aeolian deposits, it is likely that the Navajo Sandstone was deposited with a higher rate of sand supply than that of the present-day Sahara Desert (Kocurek, 2003), which may have enabled the preservation of orbital-scale palaeoclimatic records. Nevertheless, the formation mechanisms of bounding surfaces and their responses to orbital-scale climatic changes remain uncertain even in the Quaternary, due to the stochastic noise of deposition/erosion and sampling issues (e.g., Hesse, 2016; Leighton et al., 2014; Telfer et al., 2010; Thomas and Bailey, 2017). Thus, further investigation is required to test our hypothesis.

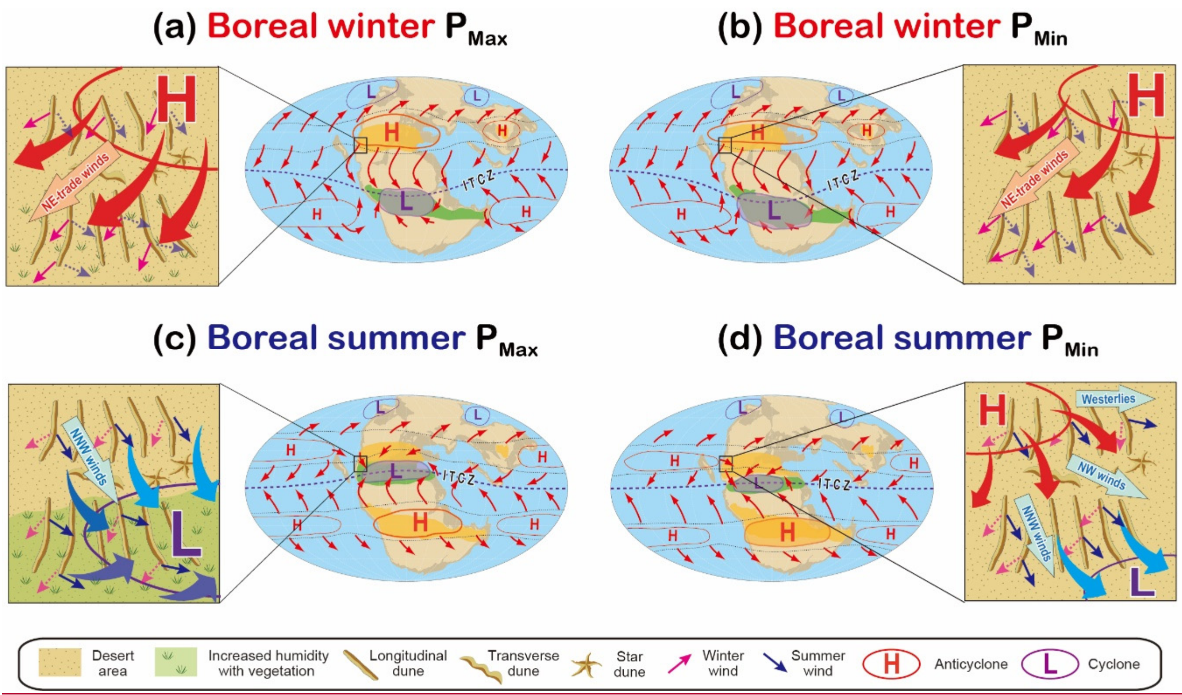

Figure 4: Schematic illustrations of orbital and seasonal changes in Pangaean atmospheric pressure ~~configuration~~ pattern and inferred dune alignments in western US during the eccentricity-modulated precession maximum (P_{Max}; a, c) and ~~precession~~ minimum (P_{Min}; b, d). Orbital-scale changes in pressure pattern~~configuration~~ are ~~illustrated~~ based on climatic model results (Winguth and Winguth, 2013). Seasonal changes in wind regimes are indicated as pink~~ish~~ (boreal winter) and blu~~eish~~ (boreal summer) arrows. During the eccentricity-modulated precession maximum, the continental low-pressure system in the boreal summer was likely reduced by a few hPa relative to the eccentricity-modulated precession minimum in response to the increase in surface temperature ~~rise~~ (Winguth and Winguth, 2013). Increased moisture and vegetation cover likely resulted in dune stabilization in the southern area during the boreal summer at the eccentricity-modulated precession maximum (c).

~~Orbital-scale changes in atmospheric pressure configuration and the relationship of these changes to dune formation in Pangaea are supported by evidence from late Quaternary dune fields in South Africa (Lancaster, 1981; Thomas and Burrough, 2016; Thomas and Bailey, 2017). Luminescence dating of dunes in the Kalahari Desert has revealed that the timing of dune accumulation varies broadly from the northeastern Kalahari (~16°–20°N; ~35 ka and later part of the Last Glacial Maximum) to the southwestern Kalahari (~23°–30°N; ~13.5 ka and Holocene) (Thomas and Burrough, 2016; Thomas and Bailey, 2017). In addition, increased dune~~

accumulation appears to be coincided with immediately after summer insolation maximum. A geomorphological study (Lancaster, 1981) has also suggested that the pattern of dune alignment in the Kalahari Desert reflects changes in atmospheric pressure regime between the Holocene and the last glacial (Stone, 2014) (**Appendix B**).

Evidence for the accumulation ages of late Quaternary dune fields in Sahara Desert (Lancaster et al., 2002; Bristow and Armitage, 2016) also has important implications for the relationship between dune stabilization and climatic humidity. Increased summer rainfall resulting from a northward shift of the ITCZ in the southern Sahara during the Early Holocene led to the so-called "Green Sahara" (Kuper and Kröpalin, 2006; Pausata et al., 2016); however, luminescence age dating of dune sands in the southern Sahara has revealed increased dune accumulation during this period, suggesting that dune stabilization proceeded in moist conditions (Bristow and Armitage, 2016). This observation is consistent with our interpretation that intense summer rainfall with vegetation and soil covers during the precession maximum likely stabilized dune-sand accumulation (Lancaster and Baas, 1998; Hesse and Simpson, 2006; Kocurek and Ewing, 2012) and resulted in the development of nodular layers and trace fossils within the Navajo Sandstone strata in the southern Utah (Chan and Archer, 2000; Loope et al., 2001; Ekdale et al., 2007). Stabilized dune sand accumulation by vegetation and soil cover likely lead to the notably thick Navajo Sandstone succession (Blakey et al., 1988; Parrish et al., 2019) in southwestern area of Colorado Plateau.

4 Conclusion

AIn summary, by comparison with of climate model reconstructions with dune slip-face azimuth data indicates thatand geological evidence of late Quaternary dune fields, reconstructed Lower Jurassic longitudinal dunes in the western US likely reflect seasonal- and orbital-scale changes in the wind regime and atmospheric pressure patternconfiguration over Pangaea. Revised palaeomagnetic data and palaeo-wind data of the present study do not support desert development and predominant westerly winds in equatorial Pangaea during the Early Jurassic, in contrast to the results ofDesert development and predominant westerly winds in equatorial Pangaea during the Early Jurassic, which is suggested by Loope et al. (2004), are not supported by revised palaeomagnetic data and the palaeo-wind regimes obtained in this study. NNE–SSW- to NNW–SSE-oriented longitudinal dunes in the central and southern parts of the study area, with and eastward-migrating uni-directional barchanoid dunes in the northernmost and southernmost parts, are interpreted to have formed as the result of superimposed integration of seasonal and orbital changes in wind regimes. The reconstructed palaeo-wind pattern at ~19°–27°N appears to be consistent with model-generated surface wind patterns and the location of the subtropical high-pressure belt. Therefore, we have solved the enigma of Pangaean atmospheric circulation patterns, such as discrepancy between model-generated wind directions and aeolian dune records as noted by Rowe et al. (2007). The results also indicate the influence of orbitally induced climate change on longitudinal dune development in subtropical Pangaea, although further chronological and sedimentological studies are required to test this hypothesis.The thick Navajo Sandstone succession in the southern area likely reflects increased moisture and resulting dune stabilization by the northward shift of the ITCZ during the precession maximum, which is consistent with evidence of dune accumulation in the "Green Sahara" during the Early Holocene.

Appendix A

Comparison between the internal structures of modern longitudinal dunes and Lower Jurassic aeolian cross-strata

Outcrop evidences of the Lower Jurassic aeolian cross-sets exhibit a marked correspondence to the internal structures of modern longitudinal dunes. Internally, modern longitudinal dunes exhibit oblique bi-directional cross-beds on each side of the dune flank and stacking of cross-beds in both directions in the central part. In central part of longitudinal dune, vertical stacking of two oblique opposing directional cross-sets result in increasing of dune height (Bristow et al., 2000; Bristow et al., 2007; Zhou et al., 2012; Telfer and Hesse, 2013; Liu and Baas, 2020).

These structural feature of modern longitudinal dunes are also observed in some outcrops in Lower Jurassic aeolian strata in western US. Some outcrops in the Zion National Park and the Arches National Park, which are located in the boundary of bi-directional slip-face directions (**Figs. 2, 3**), show zigzagging patterns and compound sets of cross-stratification (**Fig. A1**). Both outcrops exhibit vertical stacking of two oblique directional cross-beds. Thus, sedimentary structures in the Zion and Arches regions are interpreted to have been formed by vertical stacking cross-sets of longitudinal dunes.

Figure A1: Comparison between the internal structures of modern longitudinal dunes (Bristow et al., 2000) and the outcrop photographs of Lower Jurassic aeolian cross-stratifications exposed in Zion National Park (a) and Arches National Park (b). Yellow solid lines and white dashed lines indicate bounding surface of aeolian dune strata and slip-face cross-stratification, respectively. Yellow and red traces in the ground-penetrating radar (GPR) profiles of modern longitudinal dunes (Bristow et al., 2000) indicate slip-faces and unconformities, respectively.

Appendix B

Late Quaternary dune alignment and orbital changes in wind regime in South African desert

Orbitally induced changes in atmospheric pressure configuration and resulted changes in dune alignment at ~19°–27°N of Pangaea Supercontinent are supported by evidence from late Quaternary dune records in South Africa (Lancaster, 1981; Thomas and Burrough, 2016; Thomas and Bailey, 2017). Geomorphological study suggested that the NNW–SSE-oriented longitudinal dunes in the southern and western Kalahari likely formed by the interactions of austral winter northeasterlies from the continental high and summer westerlies from the South Atlantic Anticyclone (SAA) during the Holocene (Lancaster, 1981). Dune fields in the northern and eastern Kalahari were covered by vegetation as a result of increased rainfall caused by the dominance of a low-pressure cell in inland South Africa (Lancaster, 1981; Stone, 2014). In contrast, during the last glacial period,

~~the northern and eastern Kalahari dune fields experienced enhanced aridity as a result of an equatorward shift of the continental high, whereas the southern and western Kalahari dune fields became more humid as a result of moist westerly winds from the SAA (Stone, 2014) (**Fig. B1**). These evidence of orbital-scale changes in wind regime and dune development area during the Holocene and the last glacial can provide significant implication for understanding of such changes in Pangea Supercontinent during the Early Jurassic period.~~

~~**Figure B1: Schematic illustrations of changes in atmospheric pressure configuration and surface wind patterns in South Africa during the Holocene (a) and the Last Glacial Maximum (b). The purplish shaded area marks the intertropical convergence zone. White arrows indicate dominant surface winds (modified after, Stone, 2014). Bold red arrows indicate inferred wind flows, which formed longitudinal dunes. Yellowish and greenish area indicates dry and moist dune system of northern and southern Kalahari and Namib deserts, respectively. H: High pressure, L: Low pressure, SAA: South Atlantic Anticyclone, SIA: South Indian Anticyclone, AA: Arabian Anticyclone.**~~

Data availability

All data-sets are shown in the main text~~, appendix~~ and supplementary material.

Author contributions

H.H. designed this research. H.S. and H.H. conducted field survey and wrote the manuscript.

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