Shutting down dust emission during the middle Holocene drought in central Arizona

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ABSTRACT

Long-term relationships between climate and dust emission remain unclear, with two prevailing, but opposite hypotheses for impacts of climate shifts. A) Increased dust emission with increased aridity and reduced vegetation coverage. B) Emission will decrease under drier, less stormy climate as less sediments replenish dust sources by floods. Here we test these hypotheses by analyzing an ~11-m long core, archiving Holocene dust, trapped in the Montezuma Well (MW), Arizona, together with current dust sources and transport pathways. Major elements indicate that MW sediments originated from two end-members: local carbonate bedrock and external silicate-rich dust. Core sediments are similar to the adjacent silicate-rich soils accumulated over the carbonates, pointing to their eolian origin. Particle-size distributions reveal that the accumulating dust in the core are fine and coarse dust, respectively transported during winters and summers from eastern Arizona and Mojave Desert and from southern Arizona, similar to current climate systems and dust pathways. Surveys of potential dust sources indicate that current summer and winter dust sources are supply-limited and transport-limited fluvial systems, respectively. Dust

fluxes were high during the wetter phases of the Holocene when winter sources dominated. During the middle Holocene drought, dust fluxes were minimal, dominated by summer sources up to shut down as drought conditions did not produce enough floods to refill these sources with entrainable sediments. We propose that in semiarid central Arizona, dust activity is strongly connected with climate, occurring primarily during humid intervals, and enhanced by dust supplied by replenishing of sediments at dust sources.

INTRODUCTION

Associating climatic conditions with dust emission, transport, and deposition in aridlands remains indistinct. Two opposite hypotheses prevail for climate shifts from relatively humid to more arid or even towards drought. The common hypothesis involves increased dust emission with declining vegetation coverage at dust sources (Middleton, 1985; McTainsh et al., 2005; Cook et al., 2009; Marx et al., 2009) considered availability-limited sources. Opposite hypothesis assumes that under drier conditions, lacking storms usually associated with wetter conditions, dust emission decreases as sediments do not replenish the sources by occasional flooding (i.e., supply-limited and/or transport-limited sources) (Bullard and Livingstone, 2002; Routson et al., 2016; Arcusa et al., 2019); furthermore, a lack of storms may also indicate less windstorms.

Dust storms in the Sonoran Desert (Arizona, USA) are frequent, leading to fatal car accidents and health problems (Raman et al., 2014). Whereas the synoptic climatology of dust storms in Arizona is relatively known (Nickling and Brazel, 1984; Brazel et al., 1986), the geomorphic nature of dust sources in this region, and their response to changing climate, is practically unknown, both for the present and for the Holocene. During the Younger Drays (YD, 12.9-11.7 ka) and the early Holocene (11.7-8.2 ka), climate was characterized by high rainfall, changing to warmer and drier climate, known as the Middle Holocene Drought (MHD, 8.2-4.2 ka; e.g., Lachniet et al., 2020; Thompson et al., 1993), and switched to a wetter climate towards the late Holocene (<4.2 ka) (Kirby et al., 2015). Therefore, this area can serve as an ideal test of the opposing hypotheses of climate-dust relationships. To do so, we analyzed flux and properties of dust recorded by an 11.25-m-long Holocene sediment core retrieved from Montezuma Well (MW), central Arizona (Fig. 1) (Davis and Shafer, 1992). The MW is a perfect dust trap, with carbonate bedrock that stands out against the silicate-rich prevailing regional dust, and without fluvial input. Together with analyses of current dust sources and transport pathways, i.e., potential analogs for the Holocene dust sources and pathways, we evaluate the relationships between Holocene climate and dust at the millennial time scale.

RESEARCH AREA AND METHODS

The MW is a natural, circular-shape (108 m diameter) sinkhole filled with deep water (~16 m), located at the northern edge of the Sonoran Desert (Fig.1), surrounded by Miocene–early Pliocene limestone and travertine of the Verde Formation (Donchin, 1983). Current dust pathways are associated with winter cyclones and the North American Monsoon (NAM) (Adams and Comrie, 1997; Sheppard et al., 2002). The cyclones transport dust from the west, mainly during winter and the NAM from the southwest–southeast, mainly during summer (Nickling and Brazel, 1984).

Modern dust pathways were estimated by HYSPLIT-back trajectory model on 17 high dust concentration days (Table S1). Current dust sources in the region were identified using MODIS deep blue aerosol remote sensing data (Ginoux et al., 2012) ;We sampled and described the matching current dust pathway (total of 15 individual sources, 41 samples). A core was retrieved in 1985 from the northwest part of MW to avoid influence of spring discharge (Davis and Shafer, 1992). We collected 84 samples from the core and sampled the local bedrock (seven samples) and two adjacent soil profiles (six samples) (Fig S1). Age control was established using eight

C14 samples combined with published six C14 ages (Davis and Shafer, 1992). Age-depth model was processed using Bacon modelling package (Blaauw & Christeny, 2011; Table S2; Fig. S2). Bulk density was determined following Blake (1965). Major element concentrations of the core, bedrock, soils, and current dust sources samples were analyzed using an ICP-OES. Chemical scores were estimated by projecting MW core samples on calculated mixing lines (Data Repository). Particle-Size Distributions (PSD) of the core, soils and current dust sources samples were analyzed following Crouvi et al. (2008). Core samples were treated to remove carbonate and organic matter (Arcusa et al., 2019) before analysis and thus represent deposited dust (Data Repository). Dust PSD was unmixed to individual end members (Ems) using AnalySize MATLAB GUI package (Paterson and Heslop, 2015), an End Member Modeling Analysis (EMMA) software. Total dust and bedrock fluxes were calculated using Al and Ca contents, respectively, and C14 ages (Equations 1, 2 in Data Repository). Dust fluxes of individual EMs were calculated by multiplying total dust flux by the PSD EM score.

RESULTS

Unsurprisingly, current dusty days reveal two distinct dust transport pathways: (a) summer storms related to the NAM with air mass transporting mainly from the southwest and south, and (b) winter storms from the west and northwest (Fig 1). All identified current dust sources located along these pathways, are distinct geomorphic units related to fluvial systems (Data Repository). Thus, these sources are considered supply-limited sources. Sources along summer dust pathways (herein summer sources) are washes, floodplains, and alluvial fans. The washes (NH, UT, and CE) are wide (~1 km), with low vegetation and gravel cover (<20%), and a silt clay loam to loam texture. The Gila River floodplains (PL) are few km wide with 20-30% vegetation coverage that currently are cultivated; surficial sediments are silt loam to sandy loam. The alluvial fans (rest of summer sources) are composed of 1-5 m wide washes and terraces with low vegetation (10-30%)

and gravel (~5%) cover; sediments are silt loam to loamy sand. The PSDs of the summer sources are mostly unimodal, with modes at 35 ± 22 µm (n=7), 61 ± 20 µm (n=5) and 76 ± 24 µm (n=21) for the washes, floodplains, and alluvial fans, respectively. Dust sources along winter dust pathways (herein winter sources) are playas and floodplains. Kingman playa (KG) is a circular (~65 km2) basin drained by an active wash; surface is bare, with a well-developed crust of silt clay to silt loam sediments. The Colorado River floodplains (BH), used for agricultural, are 2-3 km wide with 20% vegetation cover; surficial sediments are clay loam to silt loam. These winter sources are finer than the summer sources, exhibiting unimodal PSDs with modes at 25 ± 19 µm (n=2) and 16 ± 14 µm (n=5) for the BH and KG, respectively.

Soil profiles adjacent to MW are shallow (~12 cm thick) brown lithosols with no clear horizons, and a sharp and clear contact with the carbonate bedrock. Texture is silty clay loam to silt loam with unimodal PSD; average mode is 24 ± 12 µm (n=6), and topsoil mode is 32 µm (Fig. 2); carbonate clasts are ~10%, mainly in the lower part.

The core sediments are silt to silt loam, containing variable amounts of roots and twigs, rock fragments, snails, and clams. The new C14 ages extend the published C14 ages to 13-1.2 cal ka BP (Table S2). The age-depth model (Fig. S2) reveals that accumulation rates were highest during the late Holocene (0.24 cm/yr), intermediate during the YD and the early Holocene (0.10-0.14 cm/yr), and lowest during the MHD (0.02 cm/yr). The PSDs of the core are mostly unimodal with modes from 11-66 µm, showing a general coarsening upwards trend and an average mode of 36 ± 13 µm (n=49), similar to an adjacent soil (Fig. 2). The EMMA reveals three distinct dust modes (Fig. 2), at 13 µm (EM1), 34 µm (EM2), and 75 µm (EM3). The two higher EMs are coarse dust and EM1 is fine dust. The scores of these two dust fractions (EM1 and EM2+3) oscillate in the lower parts of the core during the YD (Fig. 4), but towards and during the MHD, the coarse fraction (EM2+3) dominates the PSD, a pattern that continues also during the late Holocene.

The core samples lie along a mixing line between two distinct compositions (Fig. 3): (a) local bedrock, Ca rich and Al and Fe poor, and (b) dust, Ca poor and Al and Fe rich, represented by samples taken from current dust sources in Arizona (this study) and from the Mojave Desert (Reheis et al., 2009). Summer and winter sources slightly differ in their Al-Ca-Fe values; winter sources resemble the Mojave Desert values. Similar to the core sediments, the adjacent soils lie along this mixing line, but closer to the bedrock composition. Calculated winter/summer scores reveal low values of winter dust during the YD, switching towards high values during the early Holocene, an opposite trend to the PSD scores (Fig 4). Summer dust dominates the rest of the core, resembling the PSD scores.

Total dust flux is high (0.2-0.4 g/cm2/yr) during the YD and early Holocene (Fig 4), dominated by fine dust (EM1). Towards and during the MHD, total dust flux dramatically decreases to the lowest recorded fluxes (0.01-0.1 g/cm2/yr), originated mostly from coarse dust (EM 2+3). Total flux increased towards late Holocene, dominated by coarse dust. Pulses of MW escarpment contribution (Fig 4) are not correlated with dust fluxes and show high values at 9.5, 7 and 2 ka, in accordance with rock fragments in the core.

DISCUSSION

Dust Sources in Central Arizona

The similarity between the PSD and chemical compositions of the core and soils supports our assumption that the siliceous sediments in the core are of external origin. Moreover, the three calculated PSD EMs of the core generally fit the PSDs of surficial sediments sampled in current dust sources: The coarse EMs fit the summer sources located 180-300 km south and southwest of MW (EM2 fit the washes and EM3 fit the alluvial fans and Gila River floodplains). The fine EM fits winter sources (Kingman Playa and Colorado River floodplain) located 2270 30 km west and northwest of MW. The PSDs of Mojave Desert dust sources vary (Reheis et al., 2009), but given their relatively long transport distance (~400 km; Fig. 1), we consider them as contributing mainly to EM1. Furthermore, Mojave Desert sources are chemically similar to the winter sources in Arizona (Fig 3).

Independent observations support these interpretations: Modern dust traps in eastern Colorado Plateau have higher amounts of <10 µm dust at winters compared with coarser dust at summers (Reheis & Urban, 2011). Fine dust was observed being transported at least 400 km from western Mojave Desert eastwards towards Arizona (Reheis et al., 2002), whereas coarse dust settles within few tens of kilometers (Reheis & Rolf, 1995). Finally, theoretical relationship between wind properties and grain size indicates that 35-60 µm grains travel 180-300 km only during intensive haboob- type storms (Tsoar and Pye, 1987) that are typical to the NAM, but are absent in current winter dust storms (Raman et al., 2014). Thus, only fine dust from the Mojave Desert can reach MW under current winter storms conditions; coarse dust can be transported to MW during haboobs that characterize the NAM.

Temporal Changes in Dust Flux

Dust fluxes during the YD are the highest (Fig. 4), matching reconstructed dust fluxes in the Colorado Plateau (Arcusa et al., 2019). We propose that these high fluxes are related to the gradual drying of lakes in the Mojave Desert during deglaciation (Enzel et al., 2003), exposing erodible sediments and changing these basins into transport-limited dust sources. Frequent winter storms, related to a more southern position of the polar jet, resulted in increased rainfall and flooding replenishing these sources (Enzel et al., 2003; Asmerom et al., 2010). During the early Holocene dust fluxes decreased to about one half of the YD values (Fig. 4), and were dominated by summer sources, indicating increased NAM and decreased winter dust pathways. Climate remained relatively humid, and NAM increasingly dominating (Kirby et al., 2015). The transition towards and during the MHD was associated with an increase of the NAM activity and a decrease in winter storms (Metcalfe et al., 2015), which portrays an arid climate (Davis and Shafer, 1992; Macdonald et al., 2016; Lachniet et al., 2020). At MW, total dust fluxes became extremely low (Fig. 4). These conditions led to drying of the Mojave Desert lakes, transforming them to supply-limited (dry playas) (Enzel et al., 2003), or availability-limited (wet playas) sources (Reynolds et al., 2007). This shift can explain the gradual decrease in dust flux. At that time, coarse dust (Reynolds et al., 2006) and low dust fluxes (Arcusa et al., 2019) were observed in the Colorado Plateau. Towards the late Holocene, the area experienced wetter and colder conditions (Polyak and Asmerom, 2001; Kirby et al., 2015) resulting in higher dust fluxes, dominated by summer, supply-limited sources. At that time, increased episodes of alluvial activity were documented (e.g., Harden et al., 2010).

Throughout the YD and early Holocene, PSD and chemistry scores are uncorrelated. A probable explanation is that the higher rainfall during the YD and early Holocene increased partial leaching of elements at dust sources.

Drought Decreases Dust Emission

During the MHD, dust fluxes are minimal and dust sources in the region, both winter and summer, are in supply-limited state. We propose that the low frequency of storms resulted in lower-frequency of floods and windy days, and therefore, negligible supply of sediments to the fluvial systems; thus, shutting off these supply-limited dust sources. Action of water is crucial for creating dust, as fluvial systems supply weathered sediments that settle on top of alluvial fans, washes, and playas, where they dry and become available for eolian transport. Our findings reinforce the conceptual framework of Bullard and Livingstone (2002) that supply-limited dust sources boost production during relatively humid climate, and are less active during drought intervals.

SUMMARY

The MW records changing Holocene dust fluxes and sources, revealing millennial-scale summer/winter paleoclimate reconstruction for central Arizona. The middle Holocene drought shut off the supply-limited dust sources, generating very low dust accumulation rates. Our study shows that dust activity in Southwestern USA is controlled by the combination of wet-to-arid climate and the paleohydrology of dust sources, i.e., whether they are supply-, availability-, or transport-limited. Thus, studies of current and paleo dust should account for the relationship between these two factors for characterizing and estimations of dust activity at a given region.

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[1]GSA Data Repository item 201Xxxx, includes method and raw data description of MW core and its geological endmembers, is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org.

FIGURE CAPTIONS

Figure 1. A. The main physiographic units in the SW USA, Montezuma Well (MW) location, and current dust transport pathways. B. Topographic map of the study area with main cities and rivers, current dust sources identified using remote sensing and classified by their geomorphic nature, and samples location and name (Data repository). Identified current dust transport pathways are marked (summer-red, winter-blue). C. Photo of MW.

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MW summer EM (dashed red) results from EMMA and summer dust sources (black), from right to left – alluvial fan (GR), flood plain (PL) and wash (NH). Winter fit includes MW winter EM (dashed blue) and winter dust sources (black), from right to left – flood plain (BH) and playa (KG).

Figure 3. Triangular plot Ca-Al-Fe. All MW samples and adjacent soil (S) lay along two mixing lines between the bedrock and the summer and winter dust endmembers.

Figure 4. A. The MW stratigraphy chart (rock fragments- gray); B. Aridity index estimated from archives in the SW USA (Lachniet et al., 2020); C. The PSD EMs calculated by EMMA; D. Chemistry scores calculated based on Fig. 3; E.D. Total dust flux and PSD EMs fluxes, and F. Bedrock flux.

REFERENCES CITED

1. Adams, D.K., and Comrie, A.C., 1997, The North American Monsoon: Bulletin of the American Meteorological Society, v. 78, p. 2197–2213, doi:10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2.
2. Arcusa, S.H., Mckay, N.P., Routson, C.C., and Munoz, S.E., 2019, Dust-drought interactions over the last 15 , 000 years : A network of lake sediment records from the San Juan Mountains , Colorado: The Holocene, doi:10.1177/0959683619875192.
3. Asmerom, Y., Polyak, V.J., and Burns, S.J., 2010, Variable winter moisture in the southwestern United States linked to rapid glacial climate shifts: Nature Geoscience, v. 3, p. 114–117, doi:10.1038/ngeo754.
4. Blaauw, M., and Christeny, J.A., 2011, Flexible paleoclimate age-depth models using an autoregressive gamma process: Bayesian Analysis, v. 6, p. 457–474, doi:10.1214/11-BA618.
5. Blake, G.R., 1965, Bulk Density 1: Methods of soil analysis. Part 1. Physical and mineralogical properties, including statistics of measurement and sampling, p. 374–390.

6. Brazel, A.J., Nickling, W.G., and Lee, J., 1986, Effect of antecedent moisture conditions on dust storm generation in Arizona: Aeolian Geomorphology, Proceedings of the 17th Annual Binghamton Symposium, p. 261–271.
7. Bullard, J.E., and Livingstone, I., 2002, Interactions systems between aeolian and fluvial in dryland environments: Area, v. 34, p. 8–16.
8. Cook, B.I., Miller, R.L., and Seager, R., 2009, Amplification of the north american "Dust Bowl" drought through human-induced land degradation: Proceedings of the National Academy of Sciences of the United States of America, v. 106, p. 4997–5001, doi:10.1073/pnas.0810200106.
9. Crouvi, O., Amit, R., Enzel, Y., Porat, N., and Sandler, A., 2008, Sand dunes as a major proximal dust source for late Pleistocene loess in the Negev Desert, Israel: Quaternary Research, v. 70, p. 275–282, doi:10.1016/j.yqres.2008.04.011.
10. Davis, O.K., and Shafer, D.S., 1992, A Holocene climatic record for the Sonoran Desert from pollen analysis of Montezuma Well, Arizona, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 92, p. 107–119, doi:10.1016/0031-0182(92)90137-T.
11. Donchin, J.H., 1983, Stratigraphy and Sedimentary Environments of the Miocene-Pliocene Verde Formation in the Southeastern Verde Valley, Yavapai County, Arizona: [Ph.D. thesis]:Northern Arizona University,.
12. Enzel, Y., Wells, S.G., and Lancaster, N., 2003, Late Pleistocene lakes along the Mojave River, southeast California: Special Paper of the Geological Society of America, v. 368, p. 61–77, doi:10.1130/0-8137-2368-X.61.
13. Ginoux, P., Prospero, J.M., Gill, T.E., Hsu, N.C., and Zhao, M., 2012, Global-scale

attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products: Reviews of Geophysics, v. 50, doi:10.1029/2012RG000388.

14. Harden, T., Macklin, M.G., and Baker, V.R., 2010, Holocene flood histories in south-western USA: Earth Surface Processes and Landforms, v. 35, p. 707–716, doi:10.1002/esp.1983.
15. Kirby, M.E. et al., 2015, Evidence for insolation and Pacific forcing of late glacial through Holocene climate in the Central Mojave Desert (Silver Lake, CA): Quaternary Research (United States), v. 84, p. 174–186, doi:10.1016/j.yqres.2015.07.003.
16. Lachniet, M.S., Asmerom, Y., Polyak, V., and Denniston, R., 2020, Great Basin Paleoclimate and Aridity Linked to Arctic Warming and Tropical Pacific Sea Surface Temperatures: Paleoceanography and Paleoclimatology, v. 35, p. 1–22, doi:10.1029/2019PA003785.
17. Macdonald, G.M., Moser, K.A., Bloom, A.M., Potito, A.P., Porinchu, D.F., Holmquist, J.R., Hughes, J., and Kremenetski, K. V., 2016, Prolonged California aridity linked to climate warming and Pacific sea surface temperature: Scientific Reports, v. 6, p. 1–8, doi:10.1038/srep33325.
18. Marx, S.K., McGowan, H.A., and Kamber, B.S., 2009, Long-range dust transport from eastern Australia: A proxy for Holocene aridity and ENSO-type climate variability: Earth and Planetary Science Letters, v. 282, p. 167–177, doi:10.1016/j.epsl.2009.03.013.
19. McTainsh, G., Chan, Y.C., McGowan, H., Leys, J., and Tews, K., 2005, The 23rd October 2002 dust storm in eastern Australia: Characteristics and meteorological conditions: Atmospheric Environment, v. 39, p. 1227–1236,

doi:10.1016/j.atmosenv.2004.10.016.

20. Metcalfe, S.E., Barron, J.A., and Davies, S.J., 2015, The Holocene history of the North American Monsoon : ‘ known knowns ’ and ‘ known unknowns ’ in understanding its spatial and temporal complexity: Quaternary Science Reviews, v. 120, p. 1–27, doi:10.1016/j.quascirev.2015.04.004.
21. Middleton, N.J., 1985, Dust production in the Sahel (reply): Nature, v. 318, p. 488, doi:10.1038/318488b0.
22. Nickling, W.G., and Brazel, A.J., 1984, Temporal and spatial characteristics of Arizona dust storms (1965- 1980): Journal of Climatology, v. 4, p. 645–660.
23. Paterson, G.A., and Heslop, D., 2015, Geochemistry, Geophysics, Geosystems: , p. 4494–4506, doi:10.1002/2015GC006070.Received.
24. Polyak, V.J., and Asmerom, Y., 2001, Late Holocene climate and cultural changes in the southwestern United States: Science, v. 294, p. 148–151, doi:10.1126/science.1062771.
25. Raman, A., Arellano, A.F., and Brost, J.J., 2014, Revisiting haboobs in the southwestern United States: An observational case study of the 5 July 2011 Phoenix dust storm: Atmospheric Environment, v. 89, p. 179–188, doi:10.1016/j.atmosenv.2014.02.026.
26. Reheis, M.C., Budahn, J.R., and Lamothe, P.J., 2002, Geochemical evidence for diversity of dust sources in the southwestern United States RN - Geochim. Cosmochim. Acta, v. 66, no. 9, p. 1569-1587: Geochim.Cosmochim. Acta, v. 66, p. 1569–1587, doi:10.1016/S0016-7037(01)00864-X.
27. Reheis, M.C., Budahn, J.R., Lamothe, P.J., and Reynolds, R.L., 2009, Compositions of modern dust and surface sediments in the Desert Southwest, United States: Journal of Geophysical Research: Earth Surface, v. 114, p. 1–20, doi:10.1029/2008JF001009.

28. Reheis, M.C., and Rolf, K., 1995, Dust deposition in southern Nevada and Califonia, 1984-1989: Relations to climate, source area, and source lithology: Journal of Geophysical Research, v. 100, p. 8893–8918.

29. Reheis, M.C., and Urban, F.E., 2011, Regional and climatic controls on seasonal dust deposition in the southwestern U.S.: Aeolian Research, v. 3, p. 3–21, doi:10.1016/j.aeolia.2011.03.008.

30. Reynolds, R.L., Reheis, M.C., Neff, J.C., Goldstein, H., and Yount, J., 2006, Late Quaternary eolian dust in surficial deposits of a Colorado Plateau grassland: Controls on distribution and ecologic effects: Catena, v. 66, p. 251–266, doi:10.1016/j.catena.2006.02.003.

31. Reynolds, R.L., Yount, J.C., Reheis, M.C., Goldstein, H., Pat Chavez, J., Robert Fulton, John Whitney, Christopher Fuller, and Richard M. Forester, 2007, Dust Emission from Wet and Dry Playas in the Mojave Desert, USA: Earth Surface Processes and Landforms, v. 32, p. 1811–1827, doi:10.1002/esp.1515.

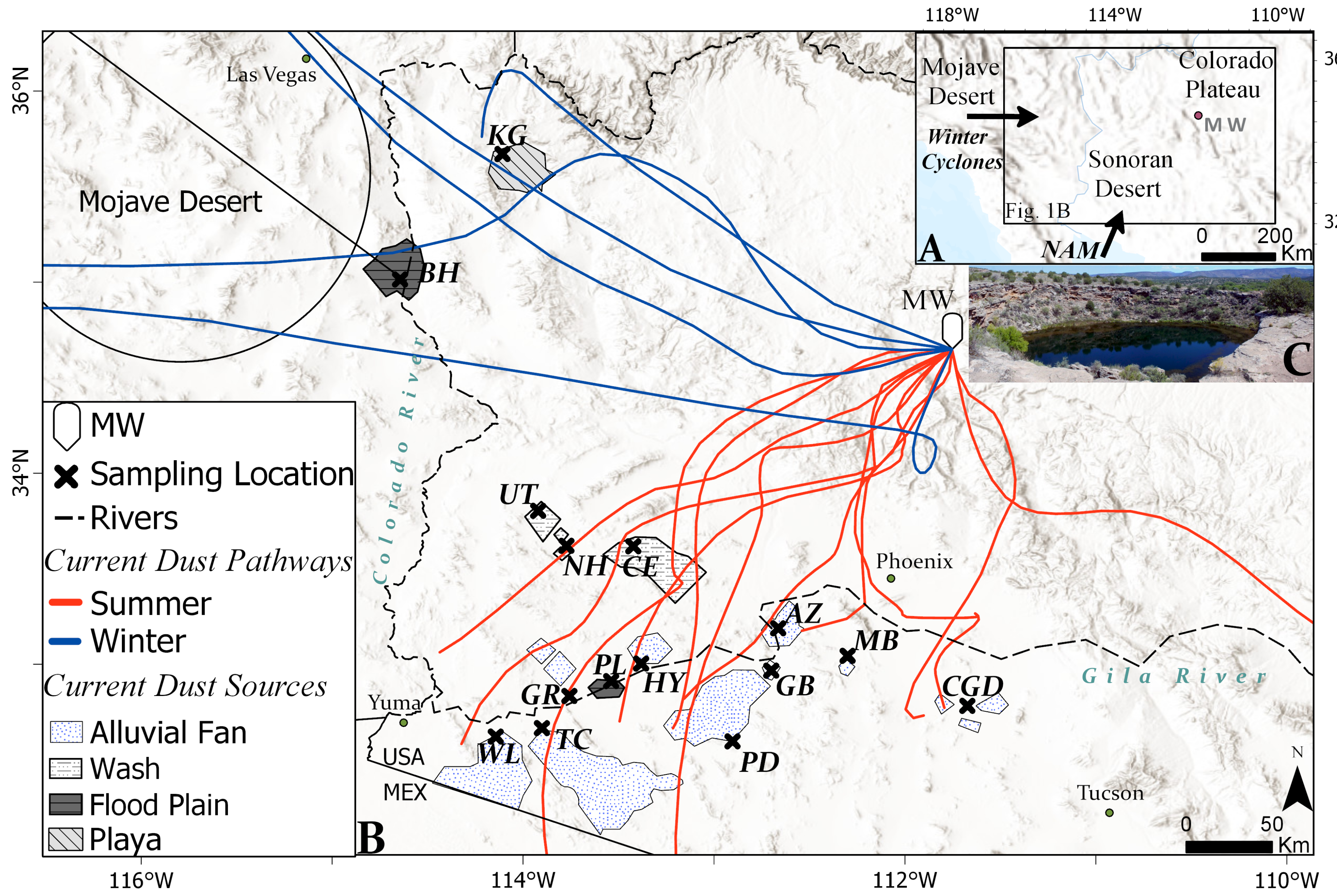
32. Routson, C.C., Overpeck, J.T., Woodhouse, C.A., and Kenney, W.F., 2016, Three millennia of southwestern north American dustiness and future implications: PLoS ONE, v. 11, p. 11–12, doi:10.1371/journal.pone.0149573.

33. Sheppard, P.R., Comrie, A.C., Packin, G.D., Angersbach, K., and Hughes, M.K., 2002, The climate of the US Southwest: Climate Research, v. 21, p. 219–238, doi:10.3354/cr021219.

34. Thompson, R.S., Whitlock, C., Bartlein, P.J., Harrison, S.P., Spaulding, W.G., Wright, H.E., Kutzbach, J.E., Webb, T.I.I.I. and Ruddiman, W.F., 1993, Climatic changes in the western United States since 18,000 yr BP. Global climates since the last glacial

maximum. 1993 Jun 1:468-513.: Global climates since the last glacial maximum, v. 1, p. 468–513.

35. Tsoar, H., and Pye, K., 1987, Dust transport and the question of desert loess formation: Sedimentology, v. 34, p. 139–153, doi:10.1111/j.1365-3091.1987.tb00566.x.



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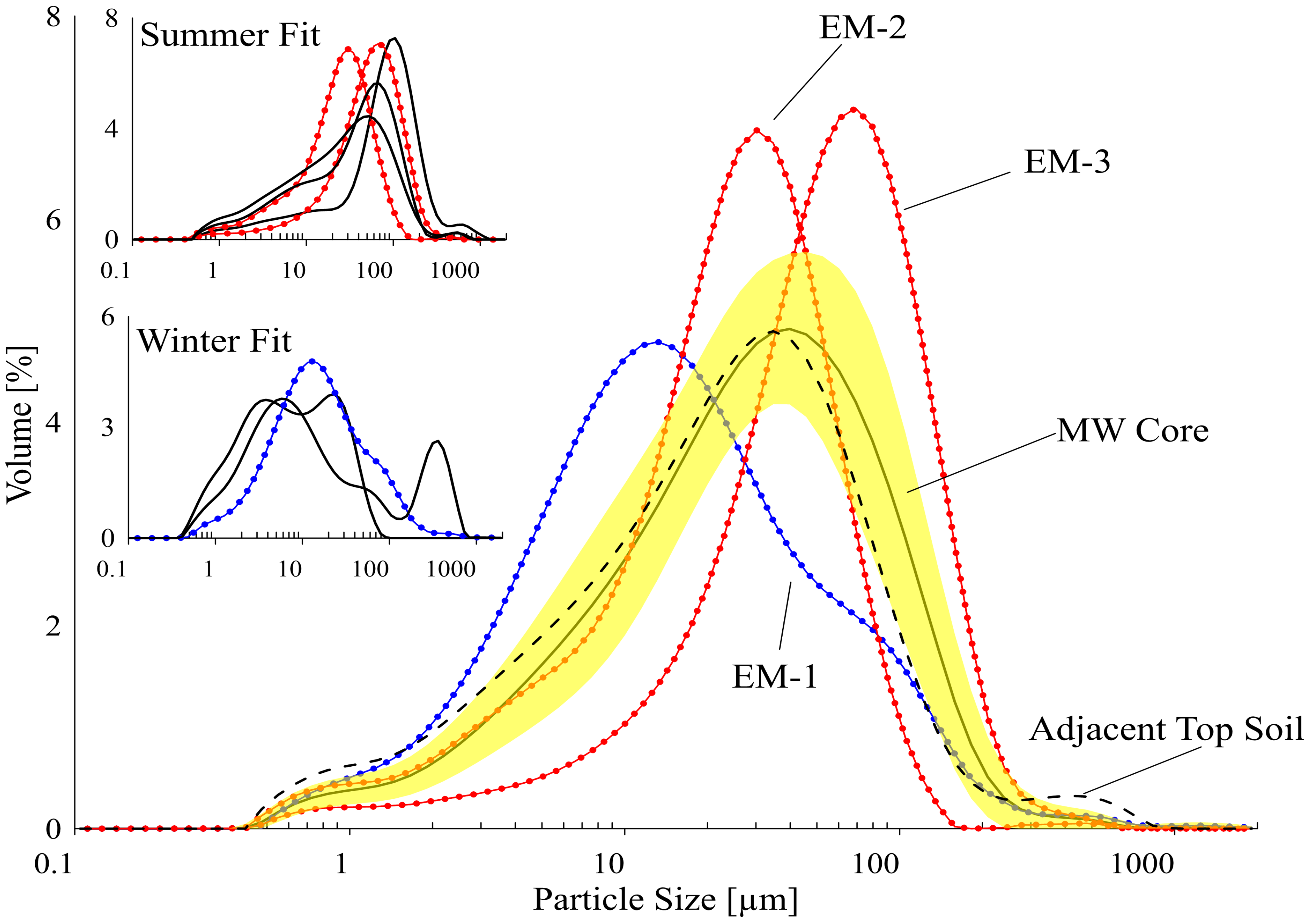

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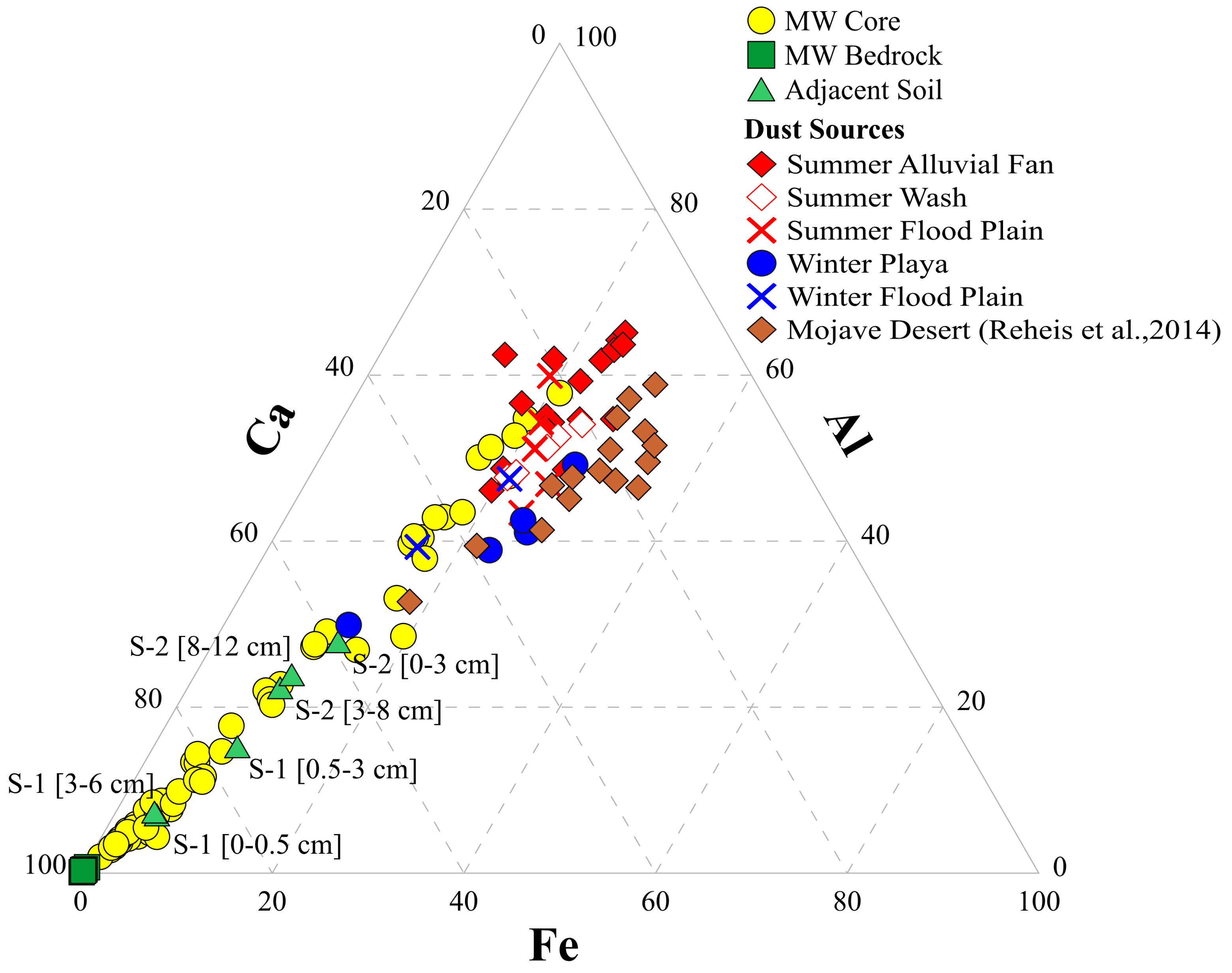

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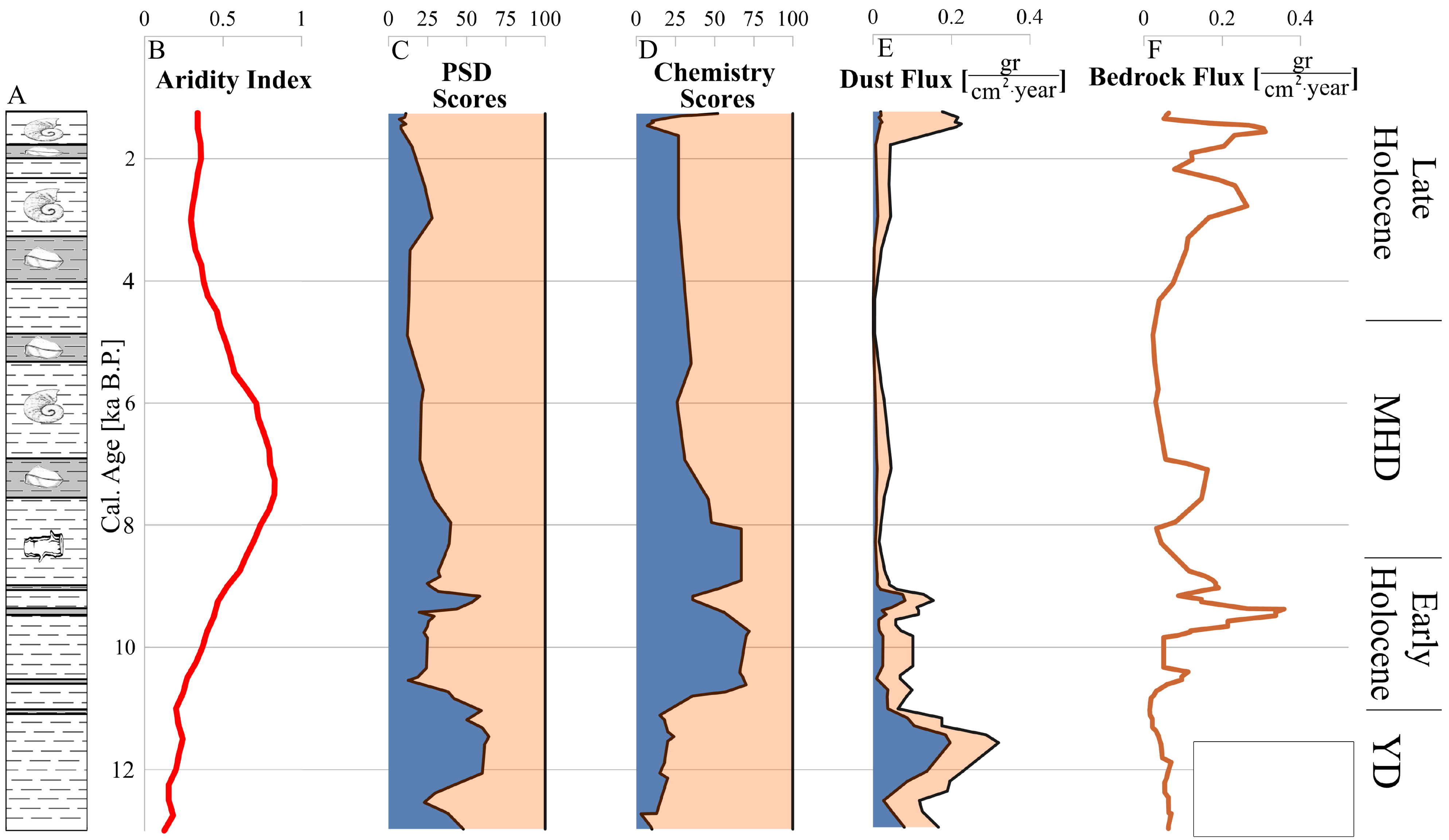

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