Paleowinds inferred from detrital-zircon geochronology of upper Paleozoic loessite, western equatorial Pangea

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ABSTRACT

U-Pb geochronology of detrital zircons from upper Paleozoic loessite (western United States) provides data bearing on atmospheric circulation within western equatorial Pangea. Zircon age spectra of four loessites from three localities representing middle Pennsylvanian (Desmoinesian) and Early Permian (Wolfcampian) time vary significantly, reflecting changing provenances attributable to temporal and spatial shifts in winds. Zircons from two Desmoinesian samples (from Arizona and Utah) show a dominant mode between 1800 and 1600 Ma, reflecting the Yavapai-Mazatzal terranes that cored the Ancestral Rockies uplifts and suggesting northeasterly winds. Both samples also contain a secondary cluster of Grenvillian grains (1300–1000 Ma), reflecting a south-southeasterly source. Ages for Wolfcampian samples (from New Mexico and Utah) differ from one another; the New Mexico loessite contains a large mode at 1700 Ma, missing in the Utah sample, reflecting their locations on opposing sides of the Ancestral Rocky Mountains, within a westerly wind regime. Inferred easterly winds for middle Pennsylvanian time match model predictions, and the presence of both northerly and southerly directions might reflect time-averaged fluctuation of the Inter-Tropical Convergence Zone. In contrast, monsoonal circulation and attendant westerly winds appear to have been well established by earliest Permian time.

Keywords: U-Pb geochronology, loessite, detrital zircons, Pangea.

INTRODUCTION

Pre-Quaternary loessite (eolian siltstone) is increasingly recognized within the upper Paleozoic of western North America (e.g., Murphy, 1987; Johnson, 1989; Soreghan, 1992; Kessler et al., 2001). Typical loess (20–70 μm) travels as far as 30 km in light to moderate windstorms, but could travel >1000 km during strong storms (Tsoar and Pye, 1987). Accordingly, loess provenance and grain-size data potentially constitute excellent proxies for atmospheric circulation patterns (wind direction and intensity).

U-Pb detrital-zircon geochronology is increasingly utilized for provenance studies of sandstones (e.g., Gehrels et al., 1991, 2000; Rainbird et al., 1992), but remains virtually untested in siltstones. Aleinikoff et al. (1999), however, applied detrital-zircon geochronology to the Quaternary Peoria Loess (of Colorado) to infer paleowind directions. In this paper we demonstrate the application of detrital-zircon geochronology as a provenance tool in upper Paleozoic loessite and its application to paleoclimate of western equatorial Pangea.

METHODS

We analyzed four upper Paleozoic loessites representing two time slices from three localities in the western United States (Fig. 1). All three sections represent significant (>100 m) accumulations of lithified loess that were dated and studied previously (Soreghan, 1992; Kessler et al., 2001; Soreghan et al., 2002). At each site, siltstone samples were collected from a stratigraphically discrete (50 cm) horizon, and, from this, 1–3 kg were processed at the Geochronology Laboratory of the Geological Survey of Canada by using standard small-sample crushing, grinding, and methylene iodide density separation techniques. A random collection of zircons of variable magnetic susceptibility was mounted in epoxy, polished to their midsections, and imaged by using backscattered-electron and cathodoluminescence techniques, by which zircons with distinct zoning, cores, overgrowths, and/or cracks were identified. U-Pb analyses were conducted by using the Sensitive High-Resolution Ion Microprobe (SHRIMP II) facility at the Geological Survey of Canada, following analytical and data-reduction procedures described by Stern (1997) (Appendix DR-A[1]).

Spot ages of individual grains are reported with 1σ analytical errors (68% confidence; Table DR-1 [see footnote 1]). The age data from concordant and nearly concordant analyses

[1]GSA Data Repository item 2002082, Appendix DR-A, Sample-preparation techniques and analytical methods; Table DR-1, SHRIMP U-Pb data for detrital zircons from upper Paleozoic loessites; and Table DR-2, Whole-rock geochemistry of acidified loessite samples from Lower Cutler Beds, Paradox basin, Utah, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, Colorado 80301, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

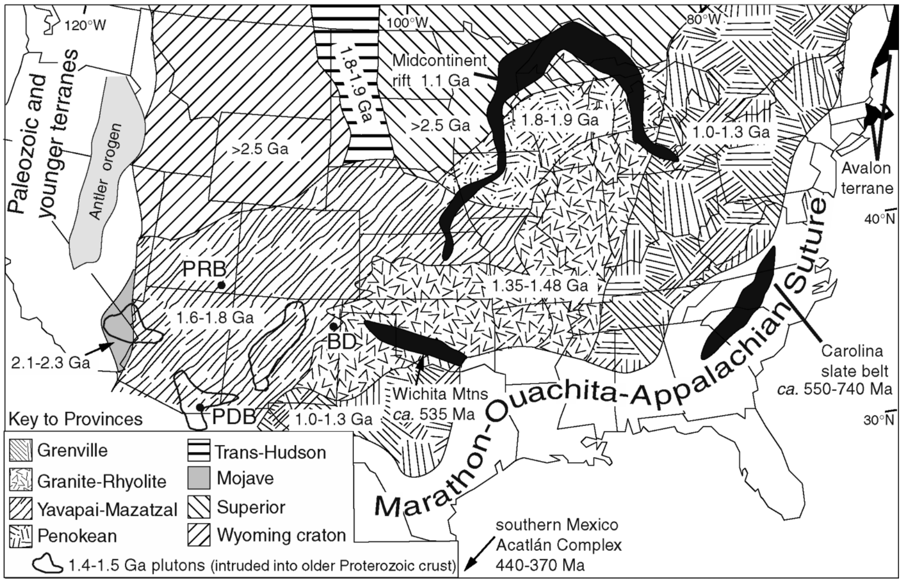

Figure 1. Basement provinces and other important age domains of North America. Dots refer to sample localities: PRB—Paradox basin, Utah; PDB—Pedregosa basin, Arizona; BD—Bravo dome, New Mexico. Two samples are Desmoinesian age (PDB and PRB-lower) and two are Wolfcampian age (BD and PRB-upper). Basement provinces are simplified from Hoffman (1989) and Van Schmus et al. (1993). Other ages are from references cited in text.

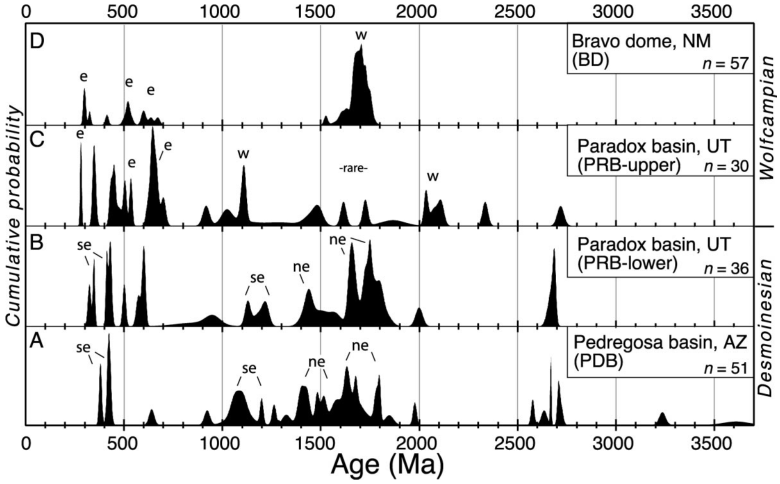

Figure 2. Cumulative probability plots of detrital-zircon ages for studied samples. Area under each curve represents summed Gaussian distribution of individual ages and associated errors for each grain. Discordant ages (by more than 5%) or grains with elevated common Pb were disregarded in these plots (Table DR-1; see text footnote 1). Small letters over peaks reflect inferred source direction of winds (in paleocoordinates) relative to interpreted source area: se—southeasterly winds; ne—northeasterly winds; w—westerly winds; e—easterly winds.

(±5% or less discordant) are depicted graphically in Figure 2 as cumulative probability histograms (Silverman, 1986); the tabulated data are presented in Table DR-1 (see footnote 1) and summarized in Table 1.

RESULTS AND INTERPRETATIONS

To apply detrital-zircon geochronology to infer eolian transport, the sources must be identified (see subsequent discussion). Owing to its resistance to abrasion, however, zircon can survive multiple erosion-deposition cycles. We argue for two reasons that zircons within sampled loessites represent first-cycle detritus derived from basement sources. First, lower Paleozoic strata in the western United States are predominantly carbonate; the limited bodies of Cambrian and Ordovician well-sorted, medium- to coarse-grained sandstone were probably not a significant source of zircon silt. Second, the loessite exhibits a low chemical index of alteration (CIA) averaging 60.6 ± 3.7 (n = 26). (Table DR-2 [see footnote 1]); the CIA is an index of chemical maturity calculated from whole-rock geochemistry of sedimentary deposits (Nesbitt and Young, 1982). Unweathered granite and granodiorite yield CIA values of 45–55, whereas average shales yield CIA values of 70–75 (Nesbitt and Young, 1982). Therefore, the whole-rock geochemistry of the loessite is indicative of minimal weathering and more reflective of derivation from crystalline basement rather than derivation from recycled sedimentary rocks. Accordingly, we interpret most of the eolian silt, and by inference most of the zircons within it, as a first-cycle deposit.

Desmoinesian Samples

Both Desmoinesian samples (Pedregosa basin, PDB; Paradox basin, PRB-lower) contain dominant detrital-zircon age modes of 1800–1600 Ma (Table 1; Fig. 2, A and B). This age range matches the regional basement (Yavapai-Mazatzal provinces) of northern Arizona, northern New Mexico, and southern Colorado (Fig. 1; Anderson et al., 1971; Karlstrom and Bowring, 1988; Bickford et al., 1989; Van Schmus et al., 1993) that was uplifted in basement-cored blocks during the late Paleozoic Ancestral Rocky Mountains orogeny (Kluth and Coney, 1981). In addition, the ca. 1510–1395 Ma zircons from both samples (Fig. 2, A and B) match the age of the granite-rhyolite basement terrane and roughly coeval granitic plutons (Fig. 1) widespread in the southwestern and midcontinental United States (Thomas et al., 1984; Van Schmus et al., 1993).

In addition, the significant population in both samples of ca. 1300–900 Ma grains (Table 1; Fig. 2, A and B) suggests derivation from Grenville basement terrane (Fig. 1). These grains may have been derived directly from Grenville basement crust of western or central Texas or northern Mexico (or recycled from miogeoclinal strata of northwestern Mexico (Gehrels et al., 1995). The cluster of grains in both samples at 430–380 Ma (Table 1; Fig. 2) is more enigmatic. Ages from these grains match the Acatlán Complex of southern Mexico, which bears ages of magmatic crystallization at 440 ± 14 Ma (U-Pb, zircon) and metamorphism at 418 ± 18 Ma (U-Pb, monazite) of the Esperanza granitoids and of late granites at 371 ± 14 Ma (U-Pb, zircon; Yañez et al., 1991; Ortega-Gutiérrez et al., 1999). The Acatlán Complex is overlain locally by alluvial strata of the Pennsylvanian-Permian Matzizi Formation (Yañez et al., 1991), suggesting that the basement was a potential sediment source during middle Pennsylvanian time.

Wolfcampian Samples

The two Wolfcampian samples (Bravo dome, BD and Paradox basin, PRB-upper) yield age spectra that differ substantially from the Desmoinesian samples and from one another (Table 1; Fig. 2, C and D). Basement ages of ca. 2200–2000 Ma represented by zircons in PRB-upper sample (Fig. 2C) are rare in the United States, but have been inferred in the Mojave terrane (Fig. 1; Bennett and DePaolo, 1987) and demonstrated in basement uplifts in the southern Canadian Cordillera (Ross, 1991). Alternatively, these zircons could have been recycled from Ordovician strata of the Roberts Mountain allochthon (Fig. 1), which shed sediment eastward through late Paleozoic time (Dickinson et al.,

TABLE 1. SUMMARY OF U-Pb DATES OF DETRITAL ZIRCONS FROM UPPER PALEOZOIC SILTSTONES

Locality (Sample Label) Formation	Age (Stage level)	Facies Sampled	Major Mode(s) (Ma)	Other Age Groupings (Ma)
Bravo dome, New Mexico (BD) Abo-Tubb (subsurface)	Wolfcampian (pre-Leonardian)	Loessite	1589–1774 (n = 42)	595–672 (n = 4) 504–537 (n = 4) 296–326 (n = 4)
Paradox basin, Utah (PRB-upper) Cutler Group	Wolfcampian	Loessite	628–702 (n = 6)	2036–2113 (n = 3) 1292–1023 (n = 4) 435–474 (n = 3) 347–354 (n =2) 283 ± 4 (youngest)
Paradox basin, Utah (PRB-lower) Hermosa Group	Desmoinesian	Eolian-marine	1648–1785 (n = 11)	1425–1511 (n = 4) 995–1221 (n = 4) 431–413 (n = 3) 325 ± 8 (youngest)
Pedregosa basin, Arizona (PDB) Horquilla Limestone	Desmoinesian	Eolian-marine	1573–1694 (n = 10)	1523–923 (n = 20) 428–380 (n = 6)

1983) and contains detrital zircons derived from the Peace River arch of northwestern Canada (Gehrels et al., 1995; Gehrels and Dickinson, 2000). The predominant source for the ca. 1800–1600 Ma zircons in the New Mexico sample (Fig. 2D) probably was Yavapai-Mazatzal basement of Colorado, New Mexico, and Arizona. Note, however, that very few zircons in this age range occur in the Utah sample (Fig. 2C); we discuss the significance of this subsequently.

The only viable sources for the ca. 675–600 Ma population of zircons in both samples (Table 1; Fig. 2, C and D) appear to be felsic metatuffs and associated plutonic rocks of the Carolina slate belt and/or plutonic and subordinate volcanic rocks of the Avalon terrane (Fig. 1; e.g., Aleinikoff et al., 1995), suggesting a distal eastern source. However, we can not necessarily rule out that the immediate source for these zircons was flysch recycled from the Ouachita-Marathon orogen. These ages also overlap Pan-African ages, but this would suggest an even more distal (Gondwanan) eastern to southeastern source. A cluster of zircon ages between ca. 535 and 500 Ma in both samples closely reflects the age of the Wichita Mountains igneous suite of Oklahoma (Hogan and Gilbert, 1997; Fig. 1). The youngest (late Paleozoic; Table 1) zircons likely reflect derivation from the Appalachian-Ouachita-Marathon magmatic arc (Fig. 1; Thomas et al., 1989; Wilson, 1990). Both of these source terranes reflect an easterly or southeasterly source direction.

DISCUSSION

All four upper Paleozoic loessites were located in western equatorial Pangea. Models suggest that Pangea's size and cross-latitudinal orientation likely produced seasonal cross-equatorial pressure contrasts, resulting in strongly monsoonal circulation (e.g., Kutzbach and Gallimore, 1989; Patzkowsky et al., 1991; Parrish, 1993). The detrital-zircon age data presented here yield varying age spectra, which we suggest reflect provenance changes caused by temporal and spatial evolution of atmospheric circulation patterns in western equatorial Pangea. The sources for the zircons and, by inference, for the majority of the silt, were regional basement uplifts of western and central equatorial Pangea; our data do not indicate only local sources, nor do they indicate extensive mixing during hemispheric-scale transport of the silt.

Figure 3 illustrates the inferred wind patterns for Desmoinesian and Wolfcampian time based on our detrital-zircon data. In both Desmoinesian samples, the predominant source region appears to be the Ancestral Rocky Mountains uplifts located east-northeast of the sample localities (in paleocoordinates). Predominant north-northeasterly winds for middle Pennsylvanian time match the data presented in Peterson (1988) and Parrish and Peterson (1988) for western North America and also match previous interpretations of the source for the eolian siltstone of the Pedregosa basin (Soreghan, 1992). However, both Desmoinesian samples also contain evidence for significant source regions to the south (Fig. 3). This southerly component may reflect seasonal migration of the Inter-Tropical Convergence Zone (ITCZ).

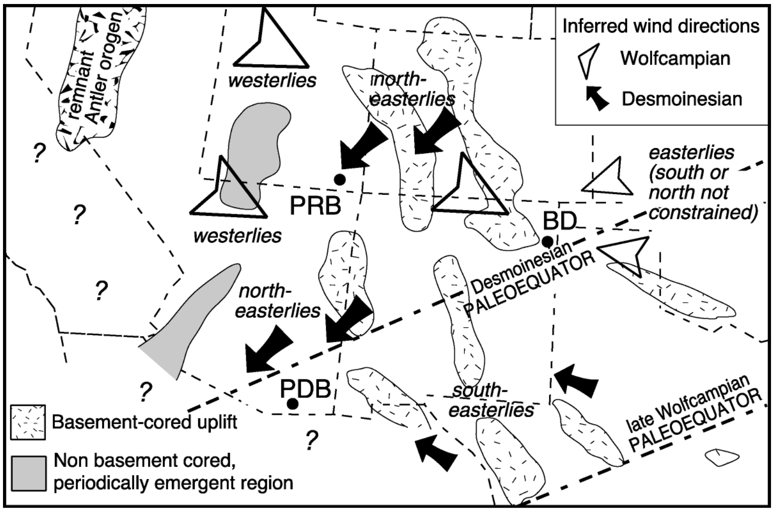

Figure 3. Inferred wind directions (arrows) for three sample localities based on detrital-zircon data. Approximate paleoequators for Desmoinesian and Wolfcampian are from Scotese (1999). Dots refer to sample localities: PRB—Paradox basin, Utah; PDB—Pedregosa basin, Arizona; BD—Bravo dome, New Mexico.

For Wolfcampian time, the detrital-zircon provenance data indicate both easterly and westerly winds (Fig. 3). The contrasting zircon age spectra between the BD and PRB-upper samples reflect their locations on opposing sides of the main Ancestral Rocky Mountains. In the Utah sample (PRB-upper), few zircons reflect derivation from Ancestral Rocky Mountains uplifts (i.e., Yavapai-Mazatzal ages), but some grains are present that possibly reflect derivation from western sources (e.g., Mojave terrane). In contrast, the New Mexico (Bravo dome, BD) sample accumulated east of the Ancestral Rocky Mountains, so westerly winds would have provided silt from these uplifts, which is consistent with the strong mode of ca. 1700 Ma zircons observed in this sample. Easterly winds, however, are also implicated on the basis of zircon age modes characteristic of the Wichita Mountains, the Appalachian-Ouachita-Marathon arc, and the 740–570 Ma (inferred Appalachian) sources. Parrish and Peterson (1988) suggested northeasterly winds (zonal) for Pennsylvanian time, but noted the possibility of summer monsoonal circulation and attendant westerly winds. Eolian cross-bed data summarized by Peterson (1988) indicate northwesterly wind directions for a number of Pennsylvanian–Early Permian dune fields in western Pangea. Cross-bed data from the Paradox basin, for example, strongly suggest northwesterly winds (Loope, 1984) during this time. For Early Permian (Sakmarian) time, Patzkowsky et al. (1991) modeled easterly (winter) to northerly or northwesterly (summer monsoonal) directions for western equatorial Pangea. Our preliminary data, therefore, are consistent with the interpretations that westerly flow associated with monsoonal circulation began by Early Permian (Wolfcampian) time.

SUMMARY AND CONCLUSIONS

Our data are consistent with the inference that atmospheric circulation was zonal within low northern latitudes of western Pangea and comprised dominant northeasterly winds and attendant southeasterly winds during Desmoinesian (middle Pennsylvanian) time. The southerly flow may reflect seasonal fluctuations of the ITCZ. For Wolfcampian (Early Permian) time, we infer a change in atmospheric circulation, marked by a significant westerly provenance signature in both samples. The signature of this westerly flow in the detrital-zircon age spectra is very different in the two Wolfcampian samples, however, because of their respective locations on opposing sides of the Ancestral Rocky Mountains. These interpretations generally support previous interpretations of paleowind patterns in western Pangea based on eolian cross-bed data and models. Unlike eolian sandstone, however, loessite preserves a record of both weak and strong winds, as evidenced in the multiple source directions within the zircon data. Further, unlike eolian sandstones, upper Paleozoic loessites occur at equatorial latitudes and offer the potential of high-resolution records of atmospheric circulation because they commonly form thick, highly cyclic records of climate fluctuations on a glacial-interglacial scale (e.g., Johnson, 1989; Soreghan et al., 1997, 2002; Kessler et al., 2001). Therefore, we suggest that detrital-zircon geochronology represents a powerful new tool for provenance and consequent paleoclimatic interpretation of ancient loessite. Additional detrital-zircon data from loessite representing other locations and time slices will allow us to more rigorously define atmospheric circulation patterns for western equatorial Pangea.

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REFERENCES CITED

Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T., and Burton, W.C., 1995, U-Pb ages of metarhyolites of the Catoctin and Mount Rogers Formations, central and southern Appalachians: Evidence for two pulses of Iapetan rifting: American Journal of Science, v. 295, p. 428–454.

Aleinikoff, J.N., Muhs, D.R., Sauer, R.R., and Fanning, C.M., 1999, Late Quaternary loess in northeastern Colorado: II. Pb isotopic evidence for the variability of loess sources: Geological Society of America Bulletin, v. 111, p. 1876–1883.

Anderson, C.A., Blacet, P.M., Silver, L.T., and Stern, T.W., 1971, Revision of the Precambrian stratigraphy in the Prescott-Jerome area, Yavapai County, Arizona: U.S. Geological Survey Bulletin 1324-6, p. 1–16.

Bennett, V.C., and DePaolo, D.J., 1987, Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping: Geological Society of America Bulletin, v. 99, p. 674–685.

Bickford, M.E., Schuster, R.D., and Boardman, S.J., 1989, U-Pb geochronology of the Proterozoic volcano-plutonic terrane in the Gunnison and Salida area, Colorado, *in* Grambling, J.A., and Tewkesbury, B.J., eds., Proterozoic geology of the southern Rocky Mountains: Geological Society of America Special Paper 235, p. 33–48.

Dickinson, W.R., Harbaugh, D.W., Saller, A.H., Heller, P.L., and Snyder, W.S., 1983, Detrital modes of upper Paleozoic sandstones derived from Antler orogen in Nevada: Implications for the nature of the Antler orogeny: American Journal of Science, v. 282, p. 481–509.

Gehrels, G.E., and Dickinson, W.R., 2000, Detrital zircon geochronology of the Antler overlap and foreland basin assemblage, Nevada, *in* Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic paleogeography and tectonics of western Nevada and northern California: Geological Society of America Special Paper 347, p. 57–64.

Gehrels, G.E., Dickinson, W.R., Ross, G.M., Stewart, J.H., and Howell, D.G., 1995, Detrital zircon reference for Cambrian to Triassic miogeoclinal strata of western North America: Geology, v. 23, p. 831–834.

Gehrels, G.E., McClelland, W.C., Samson, S.D., and Patchett, P.J., 1991, U-Pb geochronology of detrital zircons from a continental margin assemblage in the northern Coast Mountains, southeastern Alaska: Canadian Journal of Earth Sciences, v. 28, p. 1285–1300.

Gehrels, G.E., Dickinson, W.R., Darby, B.J., Harding, J.P., Manuszak, J.D., Riley, B.C.D., and Spurlin, M.S., 2000, Tectonic implications of detrital zircon data from Paleozoic and Triassic strata in western Nevada and northern California, *in* Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic paleogeography and tectonics of western Nevada and northern California: Geological Society of America Special Paper 347, p. 133–150.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A.W., and Palmer, A.R., eds., The geology of North America—An overview: Boulder, Colorado, Geological Society of America, Geology of North America, v. A, p. 447–512.

Hogan, J.P., and Gilbert, M.C., 1997, Timing of the final breakout of Laurentia: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 432.

Johnson, S.Y., 1989, Significance of loessite in the Maroon Formation (middle Pennsylvanian to Lower Permian), Eagle basin, northwestern Colorado: Journal of Sedimentary Petrology, v. 59, p. 782–791.

Karlstrom, K.E., and Bowring, S.A., 1988, Early Proterozoic orogenic assembly of tectonostratigraphic terranes in southwestern North America: Journal of Geology, v. 96, p. 561–576.

Kessler, J.L.P., Soreghan, G.S., and Wacker, H.J., 2001, Depositional and pedogenic evidence for equatorial aridity in western Pangea: Upper Paleozoic loessite of northeastern New Mexico: Journal of Sedimentary Research, v. 71, p. 818–833.

Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10–15.

Kutzbach, J.E., and Gallimore, R.G., 1989, Pangean climates: Megamonsoons of the megacontinent: Journal of Geophysical Research, v. 94, p. 3341–3357.

Loope, D.B., 1984, Eolian origin of upper Paleozoic sandstones, southeastern Utah: Journal of Sedimentary Petrology, v. 54, p. 563–580.

Murphy, K., 1987, Eolian origin of upper Paleozoic red siltstones at Mexican Hat and Dark Canyon, southeastern Utah [M.S. thesis]: Lincoln, University of Nebraska, 128 p.

Nesbitt, H.W., and Young, G.M., 1982, Early Proterozoic climates and plate motions inferred from major element chemistry of lutites: Nature, v. 229, p. 715–717.

Ortega-Gutiérrez, F., Elías-Herrera, M., Reyes-Salas, M., Macías-Romo, C., and López, R., 1999, Late Ordovician–Early Silurian continental collisional orogeny in southern Mexico and its bearing on Gondwana-Laurentia connections: Geology, v. 27, p. 719–722.

Parrish, J.T., 1993, Climate of the supercontinent Pangea: Journal of Geology, v. 101, p. 215–233.

Parrish, J.T., and Peterson, F., 1988, Wind directions predicted from global circulation models and wind directions determined from eolian sandstones of the western United States—A comparison: Sedimentary Geology, v. 56, p. 261–282.

Patzkowsky, M.E., Smith, L.H., Markwich, P.J., Engberts, C.J., and Gyllenhall, E.D., 1991, Application of the Fujita-Ziegler paleoclimate model: Early Permian and Late Cretaceous examples: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 86, p. 67–85.

Peterson, F., 1988, Pennsylvanian to Jurassic eolian transportation systems in the western United States: Sedimentary Geology, v. 56, p. 207–260.

Rainbird, R.H., Heaman, L.M., and Young, G., 1992, Sampling Laurentia: Detrital zircon geochronology offers evidence for an extensive Neoproterozoic river system originating from the Grenville orogen: Geology, v. 20, p. 351–354.

Ross, G.M., 1991, Precambrian basement in the Canadian Cordillera: An introduction: Canadian Journal of Earth Sciences, v. 28, p. 1133–1139.

Scotese, C.R., 1999, PALEOMAP animations, paleogeography, PALEOMAP Project: Arlington, University of Texas at Arlington, Department of Geology.

Silverman, B.W., 1986, Density estimation for statistics and data analysis: London, Chapman and Hall, 175 p.

Soreghan, G.S., 1992, Preservation and paleoclimatic significance of eolian dust in the Ancestral Rocky Mountains province: Geology, v. 20, p. 1111–1114.

Soreghan, G.S., Elmore, R.D., Katz, B., Cogoini, M., and Banerjee, S., 1997, Pedogenically enhanced magnetic susceptibility variations preserved in Paleozoic loessite: Geology, v. 25, p. 1003–1006.

Soreghan, G.S., Elmore, R.D., and Lewchuk, M.T., 2002, Sedimentologic-magnetic record of western Pangean climate in Upper Paleozoic loessite (Lower Cutler Beds, Utah): Geological Society of America Bulletin (in press).

Stern, R.A., 1997, The GSC sensitive high resolution ion microprobe (SHRIMP): Analytical techniques of zircon U-Th-Pb age determinations and performance evaluation: Geological Survey of Canada Current Research 1997-F, Radiogenic Age and Isotopic Studies, Report 10, p. 1–31.

Thomas, J.J., Shuster, R.D., and Bickford, M.E., 1984, A terrane of 1350- to 1450-m.y.-old silicic volcanic and plutonic rocks in the buried Proterozoic of the midcontinent and in the Wet Mountains, Colorado: Geological Society of America Bulletin, v. 95, p. 1150–1157.

Thomas, W.A., Chowns, T.M., Daniels, D.L., Neathery, T.L., Glover, L., III, and Gleason, R.J., 1989, The subsurface Appalachians beneath the Atlantic and Gulf Coastal plains, *in* Hatcher, R.D., Jr., et al., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 445–458.

Tsoar, H., and Pye, K., 1987, Dust transport and the question of desert loess formation: Sedimentology, v. 34, p. 139–153.

Van Schmus, W.R., Bickford, M.E., Anderson, J.F., Bender, E.E., Anderson, R.R., Bauer, P.W., Robertson, J.M., Bowring, S.A., Condie, K.C., Denison, R.E., Gilbert, M.C., Grambling, J.A., Mawer, C.K., Shearer, C.K., Hinze, W.J., Karlstrom, K.E., Kisvarsanyi, E.B., Lidiak, E.G., Reed, J.C., Sims, P.K., Tweto, O., Silver, L.T., Treves, S.B., Williams, M.L., and Wooden, J.L., 1993, Transcontinental Proterozoic provinces, *in* Reed, J.C., Jr., et al., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 171–334.

Wilson, J.L., 1990, Basement structural controls on Mesozoic carbonate facies in northeastern Mexico—A review, *in* Tucker, M.E., et al., eds., Carbonate platforms—Facies, sequences and evolution: International Association of Sedimentologists Special Publication 9, p. 235–255.

Yañez, P., Ruiz, J., Patchett, P.J., Ortega-Gutiérrez, F., and Gehrels, G.E., 1991, Isotopic studies of the Acatlán Complex, southern Mexico: Implications for Paleozoic North American tectonics: Geological Society of America Bulletin, v. 103, p. 817–828.

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