ATMOSPHERIC DUST AND ALGAL DOMINANCE IN THE LATE PALEOZOIC: A HYPOTHESIS

G.S. (LYNN) SOREGHAN AND MICHAEL J. SOREGHAN
School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019, U.S.A.
e-mail: lsoreg@ou.edu

ABSTRACT: **We present preliminary observations suggesting that variations among eolian dust flux, nutrient levels, and primary productivity may have been causally linked during the late Paleozoic icehouse. Modern oceanographic experiments have documented that iron is a limiting nutrient for ocean primary production, and atmospheric dust flux through the Quaternary has been linked to changes in the ''biological pump'' of the oceans. Eolian silt is remarkably abundant in upper Paleozoic strata, and the late Paleozoic is notable for the dominance of eutrophic, algal- and cement-rich bioherms and near absence of frame-building corals. Within western equatorial Pangea in particular, algal bioherms and eolian dust deposits display a close temporal and spatial relationship. Upper Paleozoic cyclothems in both the marine and terrestrial realms record high-frequency, glacial–interglacial shifts in dust flux within a world characterized overall by high atmospheric dust loads, and geochemical trends through cyclothems suggest cyclical shifts in marine primary productivity. Carbonate carbon isotopes show a strong positive excursion in the late Paleozoic, long attributed to heightened terrestrial productivity, but possibly reflecting increased marine productivity as well. We suggest that the remarkable spatial and temporal coincidence of volumetrically significant eolian siltstone and algal dominance in the late Paleozoic world reflects causation, that is, nutrient seeding of ecosystems by high atmospheric dust loads in an icehouse world. Such a connection implies probable biogeochemical repercussions in the terrestrial, oceanic, and atmospheric realms.**

THE IRON HYPOTHESIS: OBSERVATIONS FROM THE MODERN AND INFERENCES FROM THE ANCIENT

Iron is a limiting nutrient in the oceans, and stimulates primary productivity. This has been demonstrated by phytoplankton blooms resulting from iron fertilization experiments conducted in high-nutrient low-chlorophyll (HNLC) patches of ocean (''the iron hypothesis''; Martin and Fitzwater 1989; Martin et al. 1990, 1991; Martin et al. 1994; Kumar et al. 1995; Coale et al. 1996; Boyd et al. 2000), as well as coastal regions (Hutchins and Bruland 1998). The demise of modern Caribbean coral reefs is a proposed natural example of iron fertilization (Shinn et al. 2000), wherein nutrients (particularly iron) and pathogens in African dust stimulated phytoplankton and benthic algal growth as well as coral diseases in normally oligotrophic waters. Atmospheric dust provides a primary source for iron input to the ocean, and ice-core data record significant glacial-stage increases in dust flux (DeAngelis et al. 1987; Petit et al. 1990), although records from the equatorial Pacific are equivocal with respect to the timing and link between dust flux and productivity (Rea 1994). Deep-sea eolian records suggest that atmospheric dust loads have increased substantially coincident with onset of northern hemisphere glaciation and attendant drying of east central Asia commencing 2.5–3 Ma (Leinen and Heath 1981; Janecek and Rea 1983). The voluminous loess of the recent records heightened atmospheric dust loads (Pye 1984; Kukla 1987), and contrasts with the general rarity of such deposits in the geologic record. Here we outline the evidence for substantial atmospheric dust in the late Paleozoic icehouse, and suggest that the prevalence of algal bioherms unique to this interval may reflect dust-induced nutrient seeding during the late Paleozoic icehouse. This hypothesis has implications for deepening our understanding of earth system behavior over geologic time scales.

DUST IN THE LATE PALEOZOIC ICEHOUSE

The observation that iron limits primary productivity in surface waters of both open-ocean and coastal regions (references above) has significance for modern ecosystem behavior and, potentially, biosphere–atmosphere interactions through the Quaternary icehouse. To date, however, the possible implications of the ''iron hypothesis'' have yet to be applied to our understanding of paleoecologic and paleoclimatic patterns in the ancient geological record. From this perspective, the interval of the late Paleozoic (Pennsylvanian to Early Permian) is of particular interest, owing to key similarities with the latest Cenozoic (Plio–Pleistocene). Both represent global ''icehouses'' characterized by significant continental ice, repeated (glacial–interglacial) fluctuations in ice volume and atmospheric pCO_2, expansive regions of continental aridity and attendant high atmospheric dust loads, vigorous, regional-to-global monsoonal circulation, and a marked dominance of algal-based bioherms. If iron fertilization driven by atmospheric dust flux significantly influences ecosystem behavior in the modern, then we may be able to detect this effect in the ancient geological record.

Intermittent Dust Flux on a Glacial–Interglacial Scale

During the late Paleozoic, large continental ice sheets extended over the polar region of Gondwanaland (Crowell 1978, 1995), and resulted in large-amplitude sea-level changes (glacioeustasy: Heckel 1986; Veevers and Powell 1987; G.S. Soreghan and Giles 1999a). Analysis of glacial–interglacial sequences from both the shallow-marine and terrestrial realms of western equatorial Pangea (western U.S.) establishes that atmospheric dust loads fluctuated substantially between these climatic phases. Upper Paleozoic (Middle Pennsylvanian to Lower Permian) strata of the northern Pedregosa shelf (southwestern U.S.), for example, consist of shallow-marine carbonate units intercalated with demonstrably eolian-derived siltstone (G.S. Soreghan 1992). Windblown silt entered the shelf during relatively arid-phase (glacial) lowstands, and incipient phases of transgressions (G.S. Soreghan 1992; fig. 2 of G.S. Soreghan 1997). Similar carbonate–silt cycles also occur in northern Pangea (Stemmerik et al. 1998). Intermittent dust transport is also recorded in upper Paleozoic (Middle Pennsylvanian to Lower Permian) terrestrial strata of western equatorial Pangea, wherein arid- (glacial) phase eolian siltstone (loessite) sequences are punctuated by paleosols that formed during interglacial times of drastically reduced silt influx (G.S. Soreghan et al. 1997; Kessler et al. 2001; G.S. Soreghan et al. in press). Data from these studies suggest that peak dust flux in low-latitude regions of late Paleozoic Pangea occurred during glacial and incipient interglacial phases, analogous to the timing of peak atmospheric dust loads inferred from the Quaternary ice-core record (Petit et al. 1990). For the marine realm, this timing corresponds to peak dust influx at lowstand to transgressive times.

Analogous to eolian silt of the Chinese Loess Plateau, upper Paleozoic loessite contains significant iron, in the form of both iron oxide (hematitic) coats on grains, and in ultra-fine-grained (submicron) iron phases (e.g., magnetite) that precipitated within soil horizons (G.S. Soreghan et al. 1997; G.S. Soreghan et al., in press). In modern oceans, iron exists in extremely low concentrations (Martin et al. 1991), but aerosol deposition provides a key source of procurable colloidal iron (Nodwell and Price 2001) as well as dissolved iron that results from photoreduction of Fe(III) to Fe(II) during long-range eolian transport (Zhuang et al. 1992). Eolian delivery of iron-rich silt to the late Paleozoic marine realm might have similarly stimulated primary productivity.

Within upper Paleozoic marine strata, inferred glacial–interglacial fluctuations in eolian silt influx commonly coincide with geochemical evidence for low-oxygen conditions. For example, strata in basal (transgressive) positions of glacioeustatic sequences in an algal bioherm of the Orogrande basin (southwestern U.S.) consist of slightly silty, algal- and organic-rich oncoidal wackestone (G.S. Soreghan and Giles 1999b) and/or barren cementstone displaying local enrichments in ^{13}C and iron, including inclusions of Fe-rich phases (G.S. Soreghan, unpublished data; Seals et al. in press). The seafloor precipitates are similar to Precambrian and Triassic examples inferred to reflect low-oxygen, iron-rich conditions (Sumner and Grotzinger 1996; Woods et al. 1999). Further, dolomite inferred to reflect cyclic transgressive reflux in the Orogrande basin also contains elevated Fe (G.S. Soreghan et al. 2000). These features are consistent with conditions of high iron availability, potentially significant productivity, and resultant low-oxygen conditions during transgressive phases. In contrast, carbonate strata from late transgressive to highstand (interglacial) positions contain an abundant and diverse marine biota (G.S. Soreghan and Giles 1999b). Further, black ''core'' shales of classic midcontinent Pennsylvanian cyclothems record glacioeustatic transgressions and yield remarkably high organic, metal, and phosphate contents (Heckel 1977); indeed, black and gray shales of the late Paleozoic have higher iron contents relative to average Paleozoic shales (Chen and Shaffer 1984a). They also contain significant silt (Heckel 1977), up to 30% (Chen and Shaffer 1984b), which increases in abundance westward, nearer the locations of time-correlative loessite units (references below) documented in the Ancestral Rocky Mountains region (Fig. 1). Formation of midcontinent black shales

JOURNAL OF SEDIMENTARY RESEARCH, VOL. 72, NO. 4, JULY, 2002, P. 457–461
 1527-1404/02/072-457/$03.00

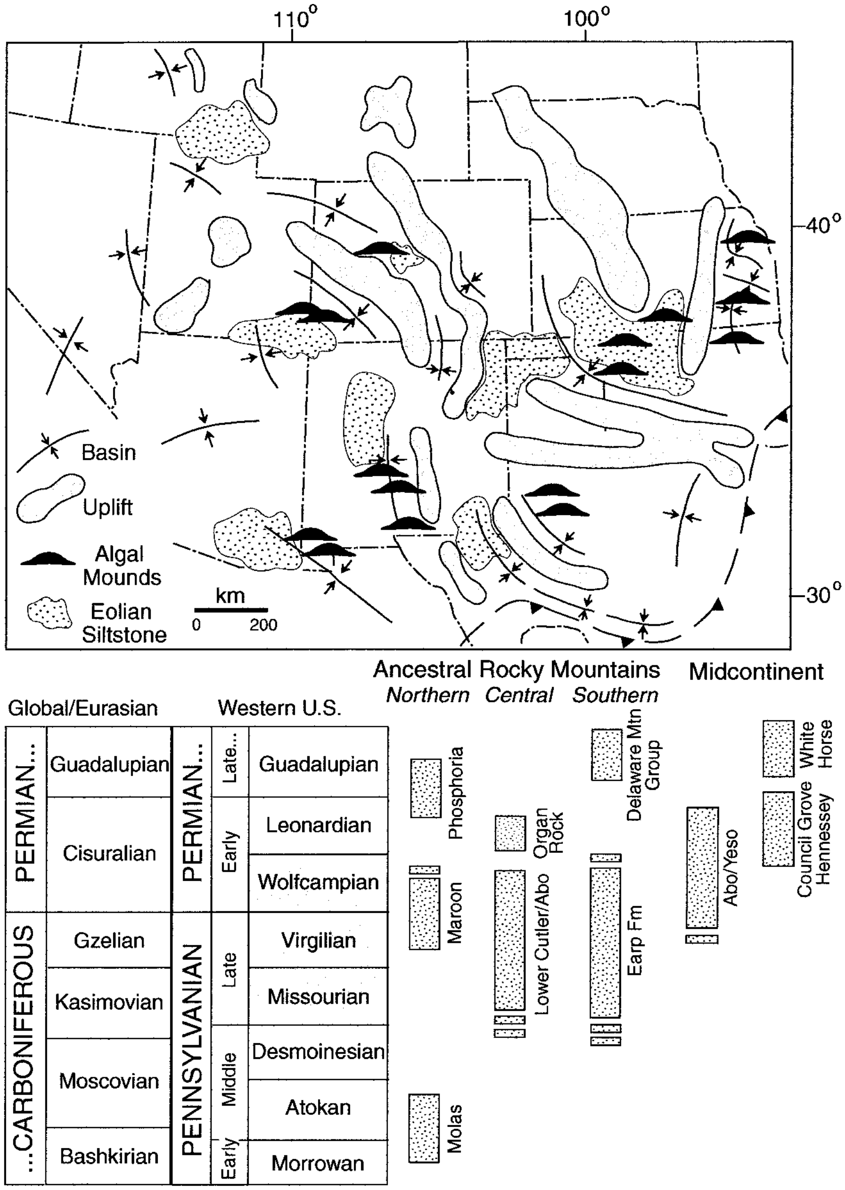

FIG. 1.—Cartoon map of western U.S. showing time-averaged distribution of documented and suspected eolian or partly eolian, and eolian–marine siltstone units (using data documented in Murphy 1987, Fischer and Sarnthein 1988, Johnson 1989, G.S. Soreghan 1992, Carroll et al. 1998, Kocurek and Kirkland 1998, Evans and Reed 2000, Stanesco et al. 2000, Kessler et al. 2001, G.S. Soreghan et al., in press, and G. Mack, personal communication 2002), and well-known algal bioherm concentrations. Distributions are shown schematized. Locations of uplifts and basins are taken from Kluth and Coney (1981). Lower diagram shows stratigraphic distributions of loessitic siltstone units. Shaded band depicts interval of inferred maximum dust flux (qualitative). Global/Eurasian stages used here and in Fig. 2 from Jin et al. (1997; Permian), and Heckel (2001; Carboniferous).

has been attributed to upwelling-induced high productivity (Heckel 1977), but some have noted probable difficulties in establishing the divergent flow necessary for upwelling in this system, and have instead suggested the organic-rich nature reflects anoxia resulting from salinity stratification (Parrish 1982). Given the evidence for lowstand- to transgressive-phase eolian silt influx in both the algal bioherm and black shale examples cited here, we suggest their organic-rich character reflects, at least in part, high productivity associated with eolian nutrient ''seeding'' analogous to that displayed in modern iron-seeding experiments.

Global Dust Flux in the Late Paleozoic

On a larger scale, the growing recognition of the prevalence of eolian silt in the late Paleozoic record of at least western equatorial Pangea (Fig. 1, and references therein), together with provenance evidence for multiple and distant source regions (M.J. Soreghan et al. 2000, M.J. Soreghan et al. in press) suggests that atmospheric dust loads were particularly high during this interval. This silt and the associated aerosols should have influenced biogeochemical cycling on an interregional to perhaps global basis. Pangea's continentality and strong monsoonal circulation system induced widespread aridity even within equatorial zones (Parrish 1993; Kessler et al. 2001) thereby fostering ''dusty'' conditions and apparently promoting the formation of desert loess in low latitudes of northern Pangea. This interval of inferred high atmospheric dust loads coincides temporally and spatially with the maximum development and abundance of algal-based biohermal systems (Fig. 2; Kiessling et al. 1999). Indeed, viewed in the context of all Phanerozoic time, the late Paleozoic (Pennsylvanian–Early Permian) was remarkable for the dominance of algae over all other reef-building biota; the Neogene, also characterized by atmospheric dustiness (Leinen and Heath 1981; Janecek and Rea 1983) is the only other time when algae have been important in organic buildups (Fig. 2; Kiessling et al. 1999).

Within late Paleozoic Pangea, algal bioherms were prevalent in western and northern Laurentia (Fig. 3; Kiessling et al. 1999). The reason for the predominance of algal-based over coral-based biohermal structures at this time and in these regions remains unresolved. Given the eutrophic nature of algal-based systems, upwelling-induced nutrient seeding is a possible explanation for their distribution, as has been proposed for modern *Halimeda* bioherms of Indonesia (Roberts et al. 1988). Analysis of paleogeographic maps, however, indicates that regions of bioherm development are commonly far from modeled upwelling zones (Fig. 3; Kiessling et al. 1999). Alternatively, continental weathering resulting from widespread Pangean orogenesis has been suggested as the source for the excess nutrient influx that fueled the algal growth of the late Paleozoic (Kiessling et al. 1999), but we suggest a variation of this hypothesis, based partly on emerging patterns from the western U.S. Here, in western equatorial Pangea, algal bioherms and eolian dust accumulations display a close temporal and spatial relationship (Fig. 1). Figure 1 focuses on documented occurrences of eolian silt, but this facies remains under-recognized, and

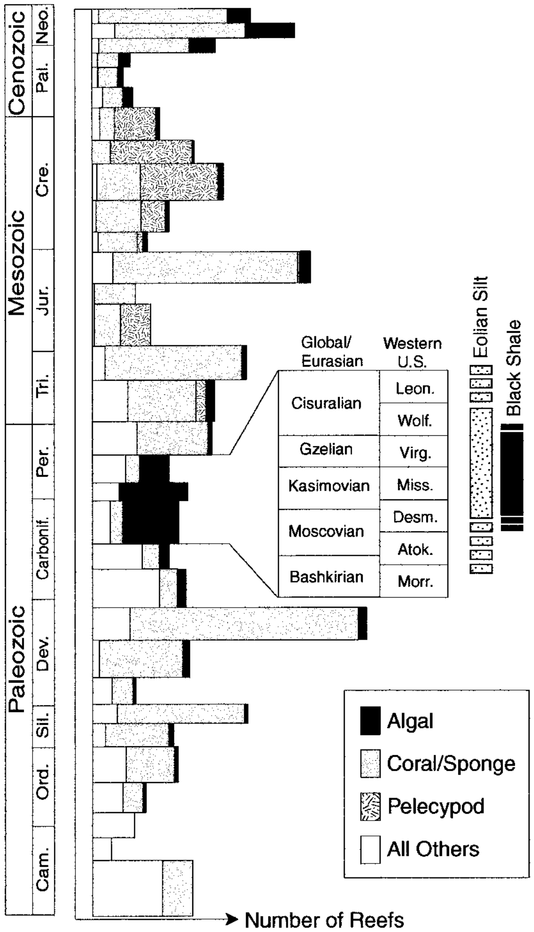

FIG. 2.—Dominant Phanerozoic reef builders (modified from Kiessling et al. 1999); note predominance of algal-based (e.g. phylloid, *Palaeoaplysinid*) biohermal systems during Late Carboniferous–Early Permian time algae (globally). Within western equatorial Pangea and subordinately, northern Pangea, this interval coincides with abundant known and suspected occurrences of eolian silt (Fig. 1; see references in Fig. 1) and ''core'' marine phosphatic black shales (from data in Heckel 1999). Note that black shales are rare after latest Pennsylvanian time, likely owing to increasingly emergent conditions through the Permian.

anomalously silty strata are prevalent in this stratigraphic interval here and elsewhere. Clearly, more data are needed to investigate possible dust inputs proximal to other well-known bioherm clusters, especially in northern Pangea. On the basis of these emerging patterns, we suggest that the algal dominance of the late Paleozoic reflects high nutrient levels derived not necessarily from upwelling, but from high atmospheric dust loads, as evidenced by the voluminous loessitic units of late Paleozoic age. Coral–sponge buildups apparently rebounded by latest Permian time (Fig. 2), after the inferred interval of maximum dust flux (Fig. 1).

High nutrient levels overall in the late Paleozoic world are potentially corroborated by the high $\delta^{13}C$ values of carbonate carbon recorded for this interval (Fig. 4). These values have long typed the late Paleozoic as a time of remarkable carbon burial, clearly reflected in the terrestrial realm by evidence for expansive and diverse land plants (Knoll et al. 1979) and resultant coal. Primary productivity in the marine realm, however, also contributed, as recorded by major petroleum source rocks of this age (Klemme and Ulmishek 1991); further, Kiessling et al. (1999) noted a close correspondence between the distributions of bioherms and source rocks in this interval. In modern times, high atmospheric dust loads deliver nutrients to stimulate primary productivity in both the marine and terrestrial systems. In the marine system, iron-seeding experiments (references above) have confirmed the importance of nutrient stimulation, and the proposed link between eolian dust influx and both nutrient seeding and reef degradation in the modern Caribbean provides a probable natural example of the influence of dust on the marine realm (Shinn et al. 2000). The terrestrial realm is equally affected, however, because atmospheric dust provides nutrients key to sustaining primary productivity in both tropical and desert soils that

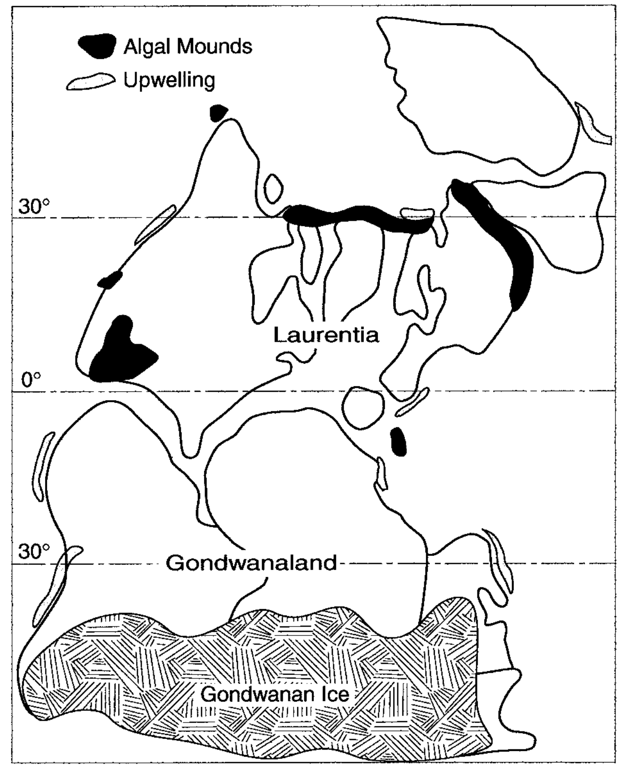

FIG. 3.—Distribution of algal bioherms and modeled upwelling zones for earliest Permian Pangea (approximate early Wolfcampian–Cirsuralian time slice), modified from Kiessling et al. (1999).

would otherwise suffer from long-term nutrient depletion (Swap et al. 1992; Chadwick et al. 1999; Reynolds et al. 2001). Therefore, high atmospheric dust loads of the late Paleozoic had the potential to contribute to primary productivity in both the terrestrial and marine realms.

SUMMARY AND CONCLUSIONS

We suggest that the remarkable spatial and temporal coincidence of volumetrically significant eolian siltstone and algal dominance in the late Paleozoic world reflects nutrient seeding of ecosystems by high atmospheric dust loads in this icehouse world. In this way, eolian dust could have stimulated significant fluctuations in atmospheric and oceanic carbon dioxide and oxygen, and oceanic pH at the glacial–interglacial scale, as well as through the greater icehouse–greenhouse transition of the latest Paleozoic. Dust-induced nutrient seeding in modern time has been suggested as a possible driver of atmospheric CO_2 levels (Martin 1990; Watson et al.

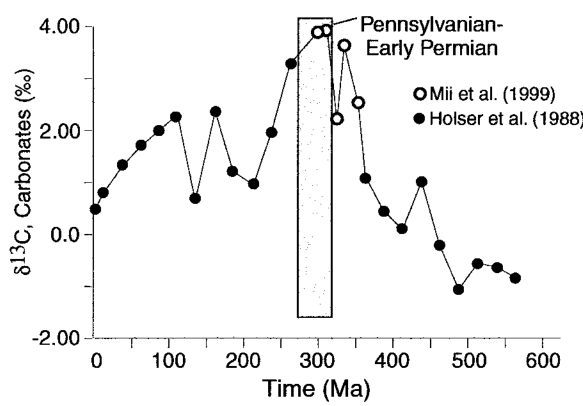

FIG. 4.—Phanerozoic trends in $\delta^{13}C$ of carbonate carbon (modified from Holser et al. 1988, with the Carboniferous segment updated from Mii et al. 1999).

2000), although this link remains controversial (Maher and Dennis 2001). The possible parallels in biogeochemical cycling between the Quaternary and late Paleozoic icehouses underscores the need for a deeper understanding of earth system behavior over geologic time scales. Clearly, this idea is provisional, but worth expressing to raise awareness of the geologic importance of dust in the pre-Cenozoic. In suggesting it, we hope to stimulate research targeted at assessing possible effects of dust in the ancient geologic record, including the global distribution and origin of eolian dust in the late Paleozoic, and variations in dust flux and marine geochemistry through glacial–interglacial cycles.

ACKNOWLEDGMENTS

Research that contributed to the concepts presented here was funded in part by the National Science Foundation (EAR-9613943, EAR-9805130, EAR-0001052), and by the Petroleum Research Fund of the American Chemical Society (ACS-PRF #s 31893-G8, 35217-AC8). We thank JSR reviewers A. Carroll, B. Kirkland, and P. Heckel for constructive comments that helped us to clarify concepts presented, and J. Southard for diligent technical editing. We also thank D. Rea and an anonymous reviewer for helpful comments on an earlier version of the manuscript.

REFERENCES

BOYD, P.W., AND 34 COAUTHORS, 2000, A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization: Nature, v. 407, p. 695–702.

CARROLL, A.R., STEPHENS, N.P., HENDRIX, M.S., AND GLENN, C.R., 1998, Eolian-derived siltstone in the Upper Permian Phosphoria Formation: implications for marine upwelling: Geology, v. 26, p. 1023–1026.

CHADWICK, O.A., DERRY, L.A., VITOUSEK, P.M., HUEBERT, B.J., AND HEDIN, L.O., 1999, Changing sources of nutrients during four million years of ecosystem development: Nature, v. 397, p. 491–497.

CHEN, P.Y., AND SHAFFER, N.R., 1984a, Petrology and mineralogy of mudrocks of the Carbondale Group (Middle Pennsylvanian), Indiana, *in* Gedsetzer, H.H.J., Nassichuk, W.W., Belt, E.S., and Macqueen R.W., eds., Neuvième Congrès Inernational de Stratigraphie et de Géologie du Carbonifère; Compte Rendu, v. 3: Carbondale, Illinois, Southern Illinois University Press, p. 641–655.

CHEN, P.Y., AND SHAFFER, N.R., 1984b, Classification of clastic sediments in Pennsylvanian coal-bearing formations emphasizing mudrock lithology, *in* Gedsetzer, H.H.J., Nassichuk, W.W., Belt, E.S., and Macqueen R.W., eds., Neuvième Congrès Inernational de Stratigraphie et de Géologie du Carbonifère; Compte Rendu, v. 3: Carbondale, Illinois, Southern Illinois University Press, p. 443–451.

COALE, K.H. AND 18 COAUTHORS, 1996, A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean: Nature, v. 383, p. 495–501.

CROWELL, J.C., 1978, Gondwanan glaciation, cyclothems, continental positioning, and climate change: American Journal of Science, v. 278, p. 1345–1372.

CROWELL, J.C., 1995, The ending of the Late Paleozoic ice age during the Permian period, *in* Scholle, P.A., Peryt, T.M., and Ulmer-Scholle, D.S., eds., The Permian of Northern Pangea, v. 1: Berlin, Springer-Verlag, p. 62–74.

DEANGELIS, M., BARKOV, N.I., AND PETROV, V.N., 1987, Aerosol concentrations over the last climatic cycle (160 kyr) from an Antarctic ice core: Nature, v. 325, p. 318–321.

EVANS, J.E., AND REED, J.M., 2000, Modification of Mississippian paleokarst (Leadville Limestone) by infiltration of Pennsylvanian loess (Molas Formation), Paradox basin, southwest Colorado (abstract): Geological Society of America, Abstracts with Programs, v. 32, p. A255.

FISCHER, A.G., AND SARNTHEIN, M., 1988, Airborne silts and dune-derived sands in the Permian of the Delaware basin: Journal of Sedimentary Petrology, v. 58, p. 637–643.

HECKEL, P.H., 1977, Origin of phosphatic black shale facies in Pennsylvanian cyclothems of Mid-Continent North America: American Association of Petroleum Geologists, Bulletin, v. 61, p. 1045–1068.

HECKEL, P.H., 1986, Sea-level curve for Pennsylvanian eustatic marine transgressive–regressive depositional cycles along Midcontinent outcrop belt, North America: Geology, v. 14, p. 330–334.

HECKEL, P.H., ed., 1999, Field Trip #8: Middle and Upper Pennsylvanian (Upper Carboniferous) Cyclothem Succession in Midcontinent Basin, U.S.A.: Kansas Geological Survey, Open-File Report 99–27, 236 p.

HECKEL, P.H., 2001, New proposal for series and stage subdivisions of Carboniferous System: Carboniferous Newsletter, v. 19, p. 12–14.

HOLSER, W.T., SCHIDLOWSKI, M., MACKENZIE, F.T., AND MAYNARD, J.B., 1988, Biogeochemical cycles of carbon and sulfur, *in* Gregor, C.B., Garrels, R.M., Mackenzie, F.T., and Maynard, J.B., eds., Chemical Cycles in the Evolution of the Earth: New York, John Wiley & Sons, p. 105–173.

HUTCHINS, D.A., AND BRULAND, K.W., 1998, Iron-limited diatom growth and Si:N uptake ratios in a coastal upwelling regime: Nature, v. 393, p. 561–564.

JANECEK, T.R., AND REA, D.K., 1983, Eolian deposition in the northeast Pacific Ocean: Cenozoic history of atmospheric circulation: Geological Society of America, Bulletin, v. 94, p. 730–738.

JIN, Y., WARDLAW, B.R., GLENISTER, B.F., AND KOTLYAR, G.V., 1997, Permian chronostratigraphic subdivisions: Episodes, v. 20, p. 10–15.

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.

KESSLER, J.L.P., SOREGHAN, G.S., AND WACKER, H.J., 2001, Equatorial aridity in western Pangea: Lower Permian loessite and dolomitic paleosols in northeastern New Mexico, U.S.A.: Journal of Sedimentary Research, v. 71, p. 818–833.

KIESSLING, W., FLÜGEL, E., AND GOLONKA, J., 1999, Paleoreef maps: Evolution of a comprehensive database on Phanerozoic reefs: American Association of Petroleum Geologists, Bulletin, v. 83, p. 1552–1587.

KLEMME, H.D., AND ULMISHEK, G.F., 1991, Effective petroleum source rocks of the world: Stratigraphic distribution and controlling depositional factors: American Association of Petroleum Geologists, Bulletin, v. 75, p. 1809–1851.

KLUTH, C.F., AND CONEY, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10–15.

KNOLL, A.H., NIKLAS, K.J., AND TIFFNEY, B.H., 1979, Phanerozoic land plant diversity in North America: Science, v. 206, p. 1400–1402.

KOCUREK, G., AND KIRKLAND, B.L., 1998, Getting to the source: Aeolian influx to the Permian Delaware basin region: Sedimentary Geology, v. 117, p. 143–149.

KUKLA, G., 1987, Loess stratigraphy in central China: Quaternary Science Reviews, v. 6, p. 191–219.

KUMAR, N., ANDERSON, R.F., MORTLOCK, R.A., FROELICH, P.N., KUBIK, P., DITTRICH-HANNEN, B., AND SUTER, M., 1995, Increased biological productivity and export production in the glacial Southern Ocean: Nature, v. 378, p. 675–680.

LEINEN, M., AND HEATH, G.R., 1981, Sedimentary indicators of atmospheric activity in the northern hemisphere during the Cenozoic: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 36, p. 1–21.

MAHER, B.A., AND DENNIS, P.F., 2001, Evidence against dust-mediated control of glacial–interglacial changes in atmospheric CO_2: Nature, v. 411, p. 176–180.

MARTIN, J.H., 1990, Glacial–interglacial CO_2 change: the iron hypothesis: Paleoceanography, v. 5, p. 1–13.

MARTIN, J.H., AND FITZWATER, S.E., 1989, Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic: Nature, v. 331, p. 341–343.

MARTIN, J.H., FITZWATER, S.E., AND GORDON, R.M., 1990, Iron deficiency limits phytoplankton growth in Antarctic waters: Global Biogeochemical Cycles, v. 4, p. 5–12.

MARTIN, J.H., GORDON, R.M., AND FITZWATER, S.E., 1991, The case for iron: Limnology and Oceanography, v. 36, p. 1793–1802.

MARTIN, J.H., AND 43 COAUTHORS, 1994, Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean: Nature, v. 371, p. 123–129.

MII, H.-S., GROSSMAN, E.L., AND YANCEY, T.E., 1999, Carboniferous isotope stratigraphies of North America: Implications for Carboniferous paleoceanography and Mississippian glaciation: Geological Society of America, Bulletin, v. 111, p. 960–973.

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

NODWELL, L.M., AND PRICE, N.M., 2001, Direct use of inorganic colloidal iron by marine mixotrophic phytoplankton: Limnology and Oceanography, v. 46, p. 765–777.

PARRISH, J.T., 1982, Upwelling and petroleum source beds, with reference to the Paleozoic: American Association of Petroleum Geologists, Bulletin, v. 66, p. 750–774.

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

PETIT, J.R., MOUNIER, L., JOUZEL, J., KOROTKEVICH, Y.S., KOTYAKOV, V.I., AND LORIUS, C., 1990, Palaeoclimatological and chronological implications of the Vostok core dust record: Nature, v. 343, p. 56–58.

PYE, K., 1984, Loess: Proceedings in Physical Geography, v. 8, p. 176–217.

REA, D.K., 1994, The paleoclimatic record provided by eolian deposition in the deep sea: the geologic history of wind: Reviews of Geophysics, v. 32, p. 159–195.

REYNOLDS, R., BELNAP, J., REHEIS, M., LAMOTHE, P., AND LUISZER, F., 2001, Aeolian dust in Colorado Plateau soils: Nutrient inputs and recent changes in source: National Academy of Science, Proceedings, v. 98, p. 7123–7127.

ROBERTS, H.H., AHARON, P., AND PHIPPS, C.V., 1988, Morphology and sedimentology of *Halimeda* bioherms from the eastern Java Sea (Indonesia): Coral Reefs, v. 6, p. 161–172.

SEALS, S.C., SOREGHAN, G.S., AND ELMORE, R.D., 2002, Submarine cements in Pennsylvanian algal mounds of the western Orogrande basin (New Mexico): Implications for changing seawater chemistry through a glacioeustatic cycle: New Mexico Geological Society Guidebook (in press).

SHINN, E.A., SMITH, G.W., PROSPERO, J.M., BETZER, P., HAYES, M.L., GARRISON, V., AND BARBER, R.T., 2000, African dust and the demise of Caribbean coral reefs: Geophysical Research Letters, v. 27, p. 3029–3032.

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., 1997, Walther's Law, climate change, and upper Paleozoic cyclostratigraphy in the Ancestral Rocky Mountains: Journal of Sedimentary Research, v. 67, p. 1001–1004.

SOREGHAN, G.S., AND GILES, K.A., 1999a, Amplitudes of Late Pennsylvanian glacioeustasy: Geology, v. 27, p. 255–258.

SOREGHAN, G.S., AND GILES, K.A., 1999b, Facies character and stratal responses to accommodation in Pennsylvanian bioherms, western Orogrande basin, New Mexico: Journal of Sedimentary Research, v. 69, p. 893–908.

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., **in press,** Sedimentologic–magnetic records of western Pangea climate in upper Paleozoic loessite (lower Cutler beds, Utah): Geological Society of America, Bulletin.

SOREGHAN, G.S., ENGEL, M.H., FURLEY, R.A., AND GILES, K.A., 2000, Glacioeustatic transgressive

reflux: stratiform dolomite in bioherms of the western Orogrande basin, New Mexico: Journal of Sedimentary Research, v. 70, p. 1315–1332.
SOREGHAN, M.J., SOREGHAN, G.S., AND HAMILTON, M.A., 2000, Paleowinds inferred from detrital zircon geochronology of Upper Paleozoic loessite, western North America (abstract): Geological Society of America, Abstracts with Programs, v. 32, p. A-255.
SOREGHAN, M.J., SOREGHAN, G.S., AND HAMILTON, M.A., Paleowinds inferred from detrital zircon geochronology of upper Paleozoic loessite, western equatorial Pangea: Geology (in press).
STANESCO, J.D., DUBIEL, R.F., AND HUNTOON, J.E., 2000, Depositional environments and paleotectonics of the Organ Rock Formation of the Permian Cutler Group, southeastern Utah, *in* Sprinkel, D.A., Chidsey, T.C., and Anderson, P.B, eds., Geology of Utah's National Parks and Monuments: Utah Geological Association, Publication 28, p. 591–605.
STEMMERIK, L., ELVEBAKK, G., NILSSON, I., AND OLAUSSEN, S., 1998, Comparison of upper Bashkirian–upper Moscovian high frequency cycles between Bjornoya and the Loppa High, western Barents Sea, *in* Gradstein, K.O., Sandvik, K.O., and Milton, N.J., eds., Sequence Stratigraphy—Concepts and Applications: Amsterdam, Elsevier Science, p. 215–227.
SUMNER, D.Y., AND GROTZINGER, J.P., 1996, Were kinetics of Archean calcium carbonate precipitation related to oxygen concentration?: Geology, v. 24, p. 119–122.
SWAP, R., GARSTAND, M., GRECO, S., TALBOT, R., AND KÅLLBERG, P., 1992, Saharan dust in the Amazon Basin: Tellus, v. 44B, p. 133–149.
VEEVERS, J.J., AND POWELL, C.M., 1987, Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive–regressive depositional sequences in Euramerica: Geological Society of America Bulletin, v. 98, p. 475–487.
WATSON, A.J., BAKKER, D.C.E., RIDGWELL, A.J., BOYD, P.W., AND LAW, C.S., 2000, Effect of iron supply on Southern Ocean CO_2 uptake and implications for glacial atmospheric CO_2: Nature, v. 407, p. 730–733.
WOODS, A.D., BOTTJER, D.J., MUTTI, M., AND MORRISON, J., 1999, Lower Triassic large sea-floor carbonate cements: Their origin and a mechanism for the prolonged biotic recovery from the end-Permian mass extinction: Geology, v. 27, p. 645–648.
ZHUANG, G., YI, Z., DUCE, R.A., AND BROWN, P.R., 1992, Chemistry of iron in marine aerosols: Global Biogeochemical Cycles, v. 6, p. 161–173.

Received 19 October 2001; accepted 11 January 2002.