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Geologic consequences of globe-encircling equatorial currents

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ABSTRACT

Many black shales, phosphorites, and cherts that formed at low paleolatitudes on the North American continent during the late Paleozoic were a direct consequence of equatorial upwelling and an equatorial undercurrent in an ocean that spanned much of the globe. In equatorial parts of modern oceans, wind stress divergence leads to high surface productivity. Sinking organic matter is remineralized in the strong, eastward-flowing equatorial undercurrent. The undercurrent thus acts as a "nutrient-trap" that becomes progressively oxygen poor and nutrient rich as it moves eastward. The late Paleozoic global ocean was 60% to 80% wider than the modern Pacific Ocean (~24 000 km total width). The nutrient-trapping equatorial current system of this globe-encircling ocean was probably anoxic and may have been sulfate reducing. Nutrient-rich, anoxic water from the undercurrent would have had direct consequences for the genesis of black-shale facies in Devonian and Pennsylvanian epicontinental seaways as well as possibly providing the source water for coastal upwelling in settings such as the Phosphoria sea.

INTRODUCTION

Ever since plate tectonic theory gained widespread acceptance, earth scientists have used the positions of continents to study and explain various aspects of Earth's climate system throughout geologic time. For example, the concentration of extensive land masses near the southern pole during the late Paleozoic is believed to have been responsible for the formation of continental ice sheets, a generally cooler climate, and sedimentary cyclothems preserved in continental interiors (e.g., Crowley and North, 1991). Assembly of the supercontinent Pangea probably led to "megamonsoonal" atmospheric circulation (Kutzbach and Gallimore, 1989), which in turn had a significant influence on the character of late Paleozoic to early Mesozoic continental sedimentary sequences (Parrish, 1993). However, the absence of continental glaciation due to the positioning of the continents at middle and low latitudes during the Cretaceous is believed to have been at least partly responsible for the equable climate of that geologic period (Barron and Washington, 1982, 1984).

Although the positions of the continents have long been recognized as a critical piece in the Earth history jigsaw puzzle, considerably less attention has been given to the consequences of differing ocean basin configurations throughout geologic time. This is at least partly due to the lack of a detailed pre-Jurassic deep-sea record. Reconstruction of this part of the geologic record must rely on deep-sea sedimentary deposits that happened to be preserved on continents or on marginal marine deposits that may or may not be representative of the character of the ocean as a whole. Deciphering the paleoceanography of pre-Jurassic oceans must therefore rely on indirect methods. For example, Parrish (1982) effectively explained the positions of upwelling zones in Paleozoic oceans as functions of continental positions and atmospheric pressure cells. In recent years, numerical modeling of ancient oceans (particularly general circulation models) has been used effectively to simulate Paleozoic paleoceanographic conditions (Crowley et al., 1989; Kutzbach et al., 1990; Moore et al., 1993).

This paper calls attention to the role that equatorial upwelling and undercurrent systems may have played in the formation of black shales, cherts, and phosphorites from the late Paleozoic Era. It is proposed here that many of these rocks in North America are a direct result of the positioning of the continents in conjunction with physical and chemical oceanographic features that are well documented in modern equatorial oceans and that were amplified in an ocean that spanned much of the globe.

NUTRIENT TRAPPING IN THE EQUATORIAL OCEAN

Modern Pacific Ocean

As the largest modern ocean basin, the Pacific Ocean will be examined in detail prior to considering how the larger, late Paleozoic ocean may have behaved. The equatorial current system of the modern Pacific consists of three westward-flowing surface currents (Northern Equatorial Current, Northern Equatorial Countercurrent, and Southern Equatorial Current) and the eastward-flowing Equatorial Undercurrent (e.g., Pickard and Emery, 1983). Upwelling at the equator is caused by the divergence of trade winds coupled with a change in sign of the Coriolis force (Ekman pumping). Surface winds and Ekman pumping are most intense in the central part of the Pacific (Fig. 1A).

The Pacific Equatorial Undercurrent is a direct result of the easterly trade winds, which raise the surface-water elevation to the west (Fig. 1B). The thermocline adjusts hydrostatically to this surface gradient, causing meridional subsurface pressure gradients (Gill, 1982). Away from the equator, these pressure gradients are geostrophically balanced by the Coriolis force. At the equator, the Coriolis force vanishes and flow is directly down the pressure gradient (toward the east). The most intense parts of the Pacific Equatorial Undercurrent coincide with the depth of the thermocline (~200 m to the west, which rises to 100 m depth in the east) (Fig. 1C). Undercurrent velocities can be as high as 1.5 m/s (Pickard and Emery, 1983).

Recent observations and modeling of the geochemistry of equatorial waters have demonstrated how westward-moving surface currents and eastward-moving undercurrents give rise to a nutrient-trapping mechanism along the equatorial axis of major ocean basins (Najjar et al., 1992). Ekman pumping brings nutrient-rich subsurface waters into the photic zone near the equator. Biologically produced particles sink below the photic zone and are advected east-

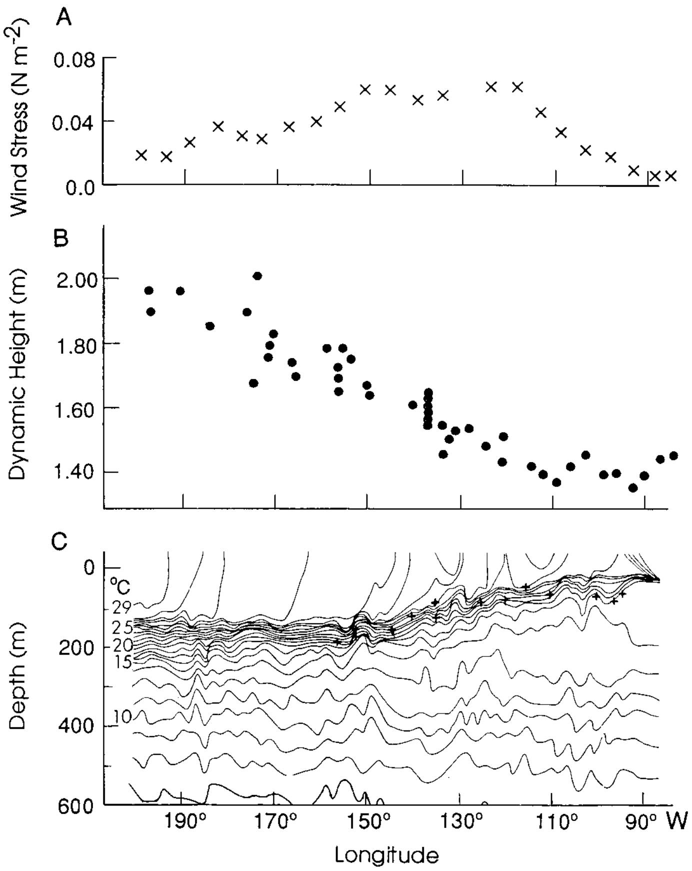

Figure 1. Surface wind shear stress (A), dynamic height (B), and subsurface temperature (C) in °C of modern equatorial Pacific region (from Knausse, 1978; Open University, 1989). Contour interval is 1 °C; crosses represent measured depth of equatorial undercurrent in (C).

ward by the equatorial undercurrent. The result is increasingly nutrient rich water to the east, which in turn increases surface productivity in the same direction (Fig. 2). The higher surface productivities further enhance the subsurface nutrient-trapping effect. Upon encountering a continental land mass, the Equatorial Undercurrent is deflected north and south. South of the equator, this nutrient-rich water forms the source for the Peru-Chile coastal upwelling system (Wyrtki, 1963; Toggweiler et al., 1991), which has some of the highest surface productivities in the world ocean (Berger, 1989).

The equatorial nutrient-trapping mechanism is found in both the Pacific and Atlantic oceans, although it is most pronounced in the Pacific. This is due in part to the higher overall nutrient concentrations in the Pacific relative to the Atlantic, but it is also a result of the Pacific Ocean's larger size, which allows the nutrient-trapping mechanism to operate over a greater longitudinal distance.

The depth of the oxygen-minimum zone in the equatorial Pacific Ocean is generally deeper (300–400 m) (Levitus, 1982) than the depth of the undercurrent (100–200 m) (Fig. 1C). In the eastern equatorial Pacific, dissolved oxygen concentrations are ~60–100 μmol/L in the equatorial undercurrent, whereas very low oxygen concentrations (<10 μmol/L) and nitrate reduction are characteristic of the deeper oxygen-minimum zone (e.g., Codispoti and Richards, 1976). Under exceptional cases off the Peruvian coast, all available oxygen and nitrate are consumed in the oxygen minimum, and hydrogen sulfide (H_2S) is formed (Dugdale et al., 1977).

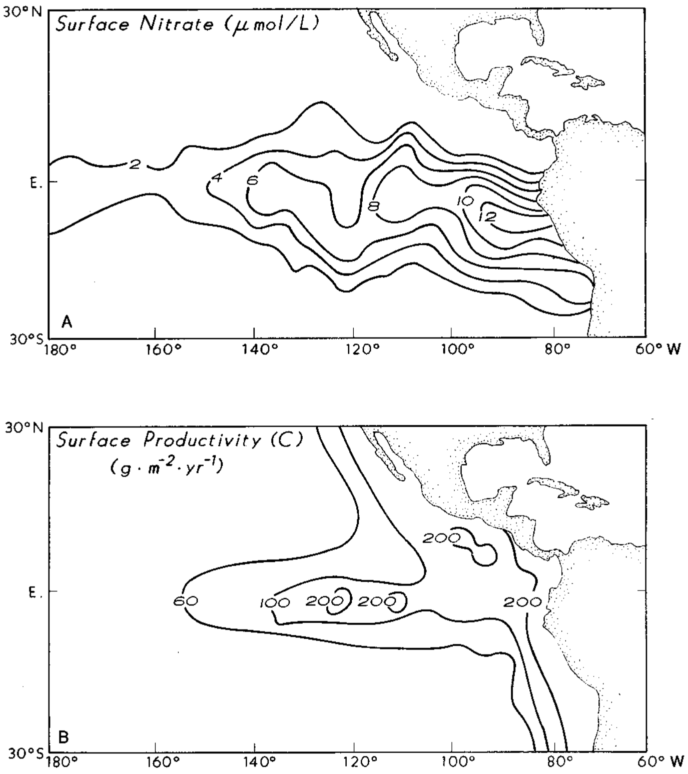

Figure 2. A: Surface nitrate concentrations in equatorial Pacific (from Toggweiler et al., 1991). B: Surface productivity in equatorial Pacific (from Berger, 1989; Najjar, 1992).

Late Paleozoic–Early Mesozoic ocean

The assembly of all the continents into a single landmass (Pangea) during the late Paleozoic to early Mesozoic and the resultant ocean (Panthalassa) that spanned much of the globe led to climatic and oceanographic conditions that may have been unique in geologic history. Earlier periods of the Paleozoic (Devonian through Mississippian) were also characterized by a single ocean that encompassed >180° of longitude (Scotese and McKerrow, 1990). The discussion presented here is intended to explain how certain aspects of marginal marine basins of North America were related to the geochemistry of a single large ocean that existed from the Devonian through the Permian. During the early Mesozoic, the Pangean continent was largely emergent (Vail et al., 1977); thus the marine sedimentary record for that period of time is not as extensive as that of the late Paleozoic.

The importance of equatorial upwelling to the formation of organic-carbon–rich rocks and phosphorites in continental settings of late Paleozoic age has been recognized by some researchers (e.g., Parrish, 1982; Witzke, 1987). What has not been fully appreciated is the geochemical consequence of the coupled equatorial upwelling-undercurrent system. This is partly because much of the work on equatorial chemical dynamics in the modern ocean has only recently appeared in the literature (e.g., Toggweiler et al., 1991; Najjar et al., 1992; Najjar, 1992).

The intensity of the equatorial nutrient-trapping phenomenon can be evaluated by considering meridional variations in oxygen from the modern Pacific Ocean (Fig. 3). Oxygen gradients at 200 m depth (within the undercurrent and slightly below it) are ~0.75 μmol/L per degree of longitude and ~1.0 μmol/L per degree of longitude at the 300 m depth. In the modern eastern equatorial Pacific, oxygen concentrations approach zero, and nitrate reduction

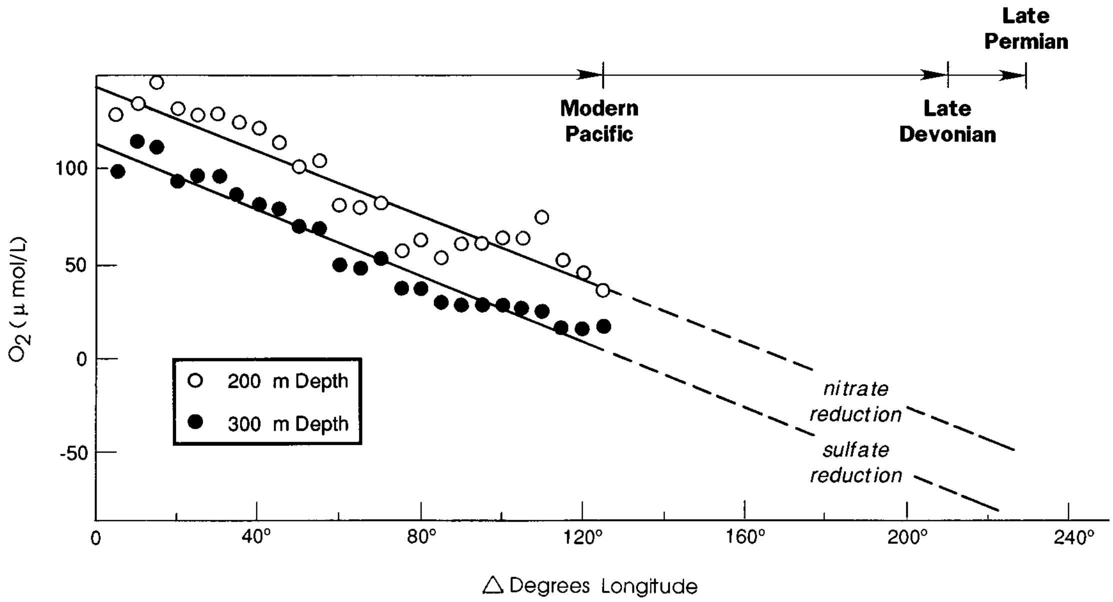

Figure 3. Oxygen concentrations as function of ocean basin width (in changes in degrees of longitude in western direction) for Pacific Ocean (data from Levitus, 1982). Dashed lines represent linear extrapolations for modern data. Negative oxygen concentrations refer to nitrate and sulfate reduction.

is widespread (Codispoti and Richards, 1976). At similar depths of the late Paleozoic–early Mesozoic ocean, nitrate would most likely be exhausted and sulfate reduction would commence (Fig. 3). As previously mentioned, sulfate reduction has been observed on occasion in the modern equatorial Pacific (Dugdale et al., 1977). In a much wider Paleozoic ocean, sulfate reduction would logically have been much more common.

Is it reasonable to expect that the chemical and physical dynamics of the globe-encircling equatorial ocean were similar to those of the modern ocean? As mentioned above, the modern Pacific Equatorial Undercurrent is a result of the zonal, easterly trade winds, which raise surface water to the west and the thermocline to the east (Fig. 1). In a larger ocean basin, these meridional sea-surface and thermocline gradients might have been larger or smaller (due to different trade-wind strength) than those in the modern Pacific and undercurrent velocities would therefore have been more or less intense. This is not critical from a geochemical standpoint because the nutrient trapping phenomenon would continue to operate over the much wider ocean basin as long as the zonal wind structure of Earth was the same as it is today.

DISCUSSION

Black-shale and phosphorite facies have long been recognized as a common feature of the Paleozoic Era. A large fraction of these deposits are Cambrian-Ordovician in age (Schopf, 1983) and may be related to anoxic episodes of the global ocean (Berry and Wilde, 1978). Certain black-shale and phosphorite episodes documented during the late Paleozoic, however, may be related to the globe-encircling, nutrient-trapping model outlined above. Some details of the more enigmatic of these deposits from three specific geologic periods are discussed here.

Late Devonian

Black shales and phosphorites are a common feature of the Late Devonian of North America. Current paleogeographic reconstructions (Witzke and Heckel, 1988; Scotese and McKerrow, 1990) show that black shales of the Catskill basin of eastern North America were located at ~lat 30°S, and would thus not be influenced by an influx of water from equatorial currents. Freshwater flow from the Acadian orogeny to the south has been evoked as a mechanism for anoxia in this basin (Ettensohn, 1985). A more extensive Late Devonian black-shale basin existed in western North America from Alaska to southern California (Witzke and Heckel, 1988). In addition to black shales and phosphorites, bedded barite is common in these rocks (Papke, 1984; Murchey et al., 1987). Open-ocean sulfate reduction at depths of 300–500 m has been advocated as a mechanism that would have enhanced dissolved barium concentrations and ultimately caused deposition of the bedded barite deposits in deep-water facies of Nevada (Jewell and Stallard, 1991; Jewell, 1994). The analysis presented here provides a mechanism for producing intermediate-depth water that was anoxic, and possibly sulfidic (Fig. 3).

Middle to Late Pennsylvanian

Cyclic deposition of black shales in the continental interior of North America from the Middle to Late Pennsylvanian is well documented (Heckel, 1977, 1991). Paleolatitude reconstructions place the Pennsylvanian black-shale belt between the equator and lat 15°N. Black-shale deposition is believed to have occurred during glacial highstands as a result of incursion of oxygen-minimum water from the open ocean in conjunction with freshwater runoff from the adjacent continent. These Pennsylvanian black shales are extraordinary for their extremely high organic carbon and metal concentrations and widespread areal extent (>500 000 km^2) (Coveney and Martin, 1983; Heckel, 1991).

High organic-carbon accumulation rates of the Pennsylvanian black shales are attributed to upwelling within the seaway (Heckel, 1977, 1991). The paleogeographic location of these rocks does suggest a relation to equatorial upwelling. It is also worth noting that the opening of the Pennsylvanian epicontinental seaway was westward facing and thus would be in position to receive nutrient-rich, oxygen-deficient (possibly anoxic) water from the equatorial current system of the Panthalassa ocean (Fig. 3).

Permian Phosphoria Formation

The Permian Phosphoria Formation of the intermountain region of North America contains more phosphorus than the modern world ocean (Piper and Codispoti, 1975). Although average phosphorus accumulation rates for the entire formation are not particularly anomalous in relation to other modern and ancient phosphogenic provinces (Filippelli and Delaney, 1992), specific members of the Phosphoria (e.g., the Meade Peak Member) have very high phosphorus accumulation rates. The paleolatitude of the Phosphoria basin is $\sim$20°N (Scotese and McKerrow, 1990). Genetic theories regarding the Phosphoria have generally involved coastal upwelling (see review by Sheldon, 1981).

The analysis presented here suggests that the source water for the Phosphoria upwelling system may have been nutrient-rich water from the globe-encircling equatorial undercurrent. The modern analog would be the Peru upwelling system, at 15°S, the source of which is the Pacific Equatorial Undercurrent (Wyrtki, 1963; Toggweiller et al., 1991); the system has surface productivities (in carbon) as high as $1400\ \mathrm{g \cdot m^{-2} \cdot yr^{-1}}$ (Packard et al., 1983). Higher nutrient concentrations in the source water during the Permian would have led to phosphorus accumulation rates higher than those observed in the modern Peru system. This is in agreement with comparative accumulation data from modern and ancient phosphogenic provinces (Filippelli and Delaney, 1992, Table 1).

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REFERENCES CITED

Barron, E. J., and Washington, W. M., 1982, Cretaceous climate: A comparison of atmospheric simulations with the geologic record: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 40, p. 103–133.

Barron, E. J., and Washington, W. M., 1984, The role of geographic variables in explaining paleoclimates: Results from Cretaceous climate model studies: Journal of Geophysical Research, v. 89, p. 1267–1279.

Berger, W. H., 1989, Global maps of ocean productivity, *in* Berger, W. H., et al., eds., Productivity in the ocean: Present and past: New York, John Wiley, p. 429–455.

Berry, W. B. N., and Wilde, P., 1978, Progressive ventilation of the oceans—An explanation for the distribution of the lower Paleozoic black shales: American Journal of Science, v. 278, p. 257–275.

Codispoti, L. A., and Richards, F. A., 1976, An analysis of the horizontal regime of denitrification in the eastern tropical North Pacific: Limnology and Oceanography, v. 21, p. 379–388.

Coveney, R. M., Jr., and Martin, S. P., 1983, Molybdenum and other heavy metals of the Mecca Quarry and Logan Quarry shales: Economic Geology, v. 78, p. 132–149.

Crowley, T. J., and North, G. R., 1991, Paleoclimatology: Oxford, United Kingdom, Oxford University Press, 339 p.

Crowley, T. J., Hyde, W. T., and Short, D. A., 1989, Seasonal cycle variations on the supercontinent Pangea: Geology, v. 17, p. 457–460.

Dugdale, R. C., Goering, J. J., Barber, R. T., Smith, R. L., and Packard, T. T., 1977, Denitrification and hydrogen sulfide in the Peru upwelling system: Deep-Sea Research, v. 24, p. 601–608.

Ettensohn, F. R., 1985, The Catskill Delta complex and the Acadian orogeny: A model, *in* Woodrow, D. L., and Sevon, W. D., eds., The Catskill Delta: Geological Society of America Special Paper 201, p. 65–77.

Filippelli, G. M., and Delaney, M. L., 1992, Similar phosphorus fluxes in ancient phosphorite deposits and a modern phosphogenic environment: Geology, v. 20, p. 709–712.

Gill, A. E., 1982, Atmosphere-ocean dynamics: Orlando, Florida, Academic Press, 662 p.

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., 1991, Thin widespread Pennsylvanian black shales of mid-continent North America: A record of a cyclic succession of widespread pycnoclines in a fluctuating epeiric sea, *in* Tyson, R. V., and Pearson, T. H., eds., Modern and ancient continental shelf anoxia: Geological Society of London Special Publication 58, p. 259–273.

Jewell, P. W., 1994, Paleoredox conditions and the origin of bedded barites along the Late Devonian North American continental margin: Journal of Geology, v. 102, p. 151–164.

Jewell, P. W., and Stallard, R. F., 1991, Geochemistry and paleoceanographic setting of bedded barite deposits, north-central Nevada: Journal of Geology, v. 99, p. 151–170.

Knausse, J. A., 1978, Introduction to physical oceanography, Englewood Cliffs, New Jersey, Prentice-Hall, 338 p.

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

Kutzbach, J. E., Guetter, P. J., and Washington, W. M., 1990, Simulated circulation of an idealized ocean for Pangean time: Paleoceanography, v. 5, p. 299–317.

Levitus, S., 1982, Climatological atlas of the world ocean: National Oceanic and Atmospheric Administration Professional Paper 13, 172 p.

Moore, G. T., Hayashida, D. N., and Ross, C. A., 1993, Late Early Silurian (Wenlockian) general circulation model-generated upwelling, graptolitic black shales, and organic-rich source rocks—An accident of plate tectonics?: Geology, v. 21, p. 17–20.

Murchey, B. L., Madrid, R. J., and Poole, F. G., 1987, Paleozoic bedded barite associated with chert in western North America, *in* Hein, J. R., ed., Siliceous sedimentary rock-hosted ores and petroleum: New York, Van Nostrand Reinhold, p. 269–283.

Najjar, R. G., 1992, Marine biogeochemistry, *in* Trenberth, K. E., ed., Climate system modeling: Cambridge, United Kingdom, Cambridge University Press, p. 241–280.

Najjar, R. G., Sarmiento, J. L., and Toggweiler, J. R., 1992, Downward transport and fate of organic matter in the ocean: Simulations with a general circulation model: Global Biogeochemical Cycles, v. 6, p. 45–76.

Open University, 1989, Ocean circulation: Oxford, United Kingdom, Pergamon Press, 238 p.

Packard, T. T., Garfield, P. C., and Codispoti, L. A., 1983, Oxygen consumption and denitrification below the Peruvian upwelling, *in* Suess, E., and Theide, J., eds., Coastal upwelling: Its sedimentary record. Part A: Responses of the sedimentary regime to present coastal upwelling: New York, Plenum Press, p. 147–173.

Papke, K. G., 1984, Barite in Nevada: Nevada Bureau of Mines and Geology Bulletin 98, 125 p.

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.

Pickard, G. L., and Emery, W. J., 1983, Descriptive physical oceanography: Oxford, United Kingdom, Pergamon Press, 249 p.

Piper, D. Z., and Codispoti, L. A., 1975, Marine phosphorite deposits and the nitrogen cycle: Science, v. 188, p. 15–18.

Schopf, T., 1983, Paleozoic black shales in relation to continental margin upwelling, *in* Suess, E., and Thiede, J., eds., Coastal upwelling: Its sediment record. Part B: Sedimentary records of ancient coastal upwelling: New York, Plenum Press, p. 579–596.

Scotese, C. R., and McKerrow, W. S., 1990, Revised world maps and introduction, *in* McKerrow, W. S., and Scotese, C. R., eds., Paleozoic paleogeography and biogeography: Geological Society of London Memoir 12, p. 1–21.

Sheldon, R. P., 1981, Ancient phosphorites: Annual Review of Earth and Planetary Sciences, v. 9, p. 251–284.

Toggweiler, J. R., Dixon, K., and Broecker, W. S., 1991, The Peru upwelling system and ventilation of the South Pacific thermocline: Journal of Geophysical Research, v. 96, p. 6907–6924.

Vail, P. R., Mitchum, R. M., Jr., and Thompson, S. I., 1977, Global cycles of relative changes in sea level, *in* Payton, C. E., ed., Seismic stratigraphy—Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 83–97.

Witzke, B. J., 1987, Models for circulation patterns in epicontinental seas applied to Paleozoic facies of North America: Paleoceanography, v. 2, p. 229–248.

Witzke, B. J., and Heckel, P. H., 1988, Paleoclimate indicators and inferred Devonian paleolatitudes of Euramerica, *in* McMillan, N. J., et al., eds., Devonian of the world, Volume I: Regional syntheses: Canadian Society of Petroleum Geologists, Proceedings of the Second International Symposium on the Devonian System, p. 49–63.

Wyrtki, K., 1963, The horizontal and vertical field of motion in the Peru Current: Scripps Institute of Oceanography Bulletin, v. 8, p. 313–346.

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