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A Computer Animation of Continental Drift

Christopher R. SCOTESE,* Sigmund SNELSON,** William C. ROSS,**
and Linda P. DODGE**

**Department of Geophysical Sciences, University of Chicago,*
Chicago, Illinois, U.S.A.
***Shell Development Co., Bellaire Research Center,*
Houston, Texas, U.S.A.

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A computer animation of continental drift has been produced which illustrates the movements of the continents during the last 545 million years. Beginning in the Late Cambrian, the animation shows the sequence of continental collisions which by the end of the Paleozoic formed the supercontinent, Pangaea. The remainder of the film describes the breakup of Pangaea and the subsequent formation of the world's ocean basins. The animation was made at Shell Development Company, Houston, Texas. It is entitled, *Dynamic Continents*, and is black and white, silent, and runs approximately 5 min.

1. Introduction

During the past 10 years, the tectonic history of nearly every mountain belt and ocean basin has been re-interpreted in light of plate tectonic theory. Detailed maps of linear magnetic anomalies and data from the Deep Sea Drilling Project permit accurate reconstructions of the spreading histories of all the major ocean basins. These recent plate tectonic models, together with the framework provided by paleomagnetism, have been used by various workers to reassemble the past configurations of the continents.

The first set of widely accepted Phanerozoic reconstructions were made by SMITH *et al.* (1973). These maps, which showed the positions of the continents at 8 intervals since the Late Cambrian, have served as base maps for numerous geologic, biogeographic, and paleoclimatic investigations. Recently, the Mesozoic and Cenozoic reconstructions have been revised and expanded (SMITH and BRIDEN, 1977). Other reconstructions of the Paleozoic, Mesozoic, and Cenozoic have been proposed by ZONENSHAYN and GORODNITSKY (1977a, b), KANASEWICH *et al.* (1978), MOREL and IRVING (1978), IRVING (1977), and SCOTESE *et al.* (1979). Though differing in detail, these models outline the same basic pattern of Paleozoic collision and Mesozoic-Cenozoic rifting.

Though the maps are useful for plotting and interpreting a variety of geologic, biogeographic, and paleoclimatic data, they cannot capture the dynamic aspects of the plate tectonic process. In plate tectonics, subtle temporal relationships are often as important as the more obvious spatial relationships. The best way of adding the dimension of time to a set of reconstructions is by film animation.

In 1974 a film based on SMITH *et al.*, (1973) set of reconstructions was produced on the PLATO computer system at the University of Illinois in Chicago (Scotese and Baker, 1975). As a result of the success of the first film, work was begun on a new animation at Shell Development Company's Bellaire Research Center. The film described in this article is one of several animations which have been produced during the past two years.

2. Materials and Methods

The computer hardware used to generate the film consists of a Harris minicomputer, Tektronix 4014 terminal, Versatec electrostatic plotter, and Adage vector display terminal. A Bolex, 16 mm motion picture camera was interfaced with the system and the animation was filmed directly from the Adage screen.

The Adage is an interactive graphics terminal. Built-in microprocessors permit such 'hard-wired' graphics functions as 3-dimensional rotations, scaling and windowing. Hard copy of any screen display can be made using the Versatec electrostatic plotter.

Because the Adage cathode ray tube constantly updates, or refreshes, the vector display, rather than permanently store the vector positions, animation sequences can be previewed or filmed in 'real time'. The slowest link in the animation process is the 16 mm camera which films at a rate of two frames per sec. In a typical session, 3 min of animation could be filmed in a little less than one hour.

Though the film appears to be continuous it is actually composed of 24 separate animated sequences. Versatec plots of 6 frames from the animation are shown in Figs. 1–6. The data used to construct this model of Phanerozoic plate motions are described in the following section.

3. The Plate Tectonic Model

Though the overall pattern of continental motion during the Phanerozoic is known, there are times and places where crucial information is not available, or where the interpretation of data is disputed. A film does not provide a suitable format for the discussion of alternate points-of-view, nor is there any way of placing 'error bars' on the interpretations shown. In the following section, the plate tectonic model and the paleomagnetic data which were used to produce the animation will be discussed and areas of controversy outlined.

4. The Paleozoic

The paleomagnetic data and the Euler rotations used to reassemble the Paleozoic continents are described in Scotese *et al.* (1979). The pattern of Paleozoic continental movements, collisions, and paleogeographic changes is outlined in two companion papers (Ziegler *et al.*, 1979; Bambach *et al.*, 1980).

The Paleozoic reconstructions are based primarily on paleomagnetic data. Though absolute longitude cannot be determined, the relative longitudinal arrangement can in most cases be deduced from biogeographic patterns (Ziegler *et al.*, 1977), and the sequence of continental collisions. As Fig. 1 illustrates, the problem of longitudinal uncertainty was minimized during the early Paleozoic for this was a time when most of the continents occupied the same low latitudinal belt.

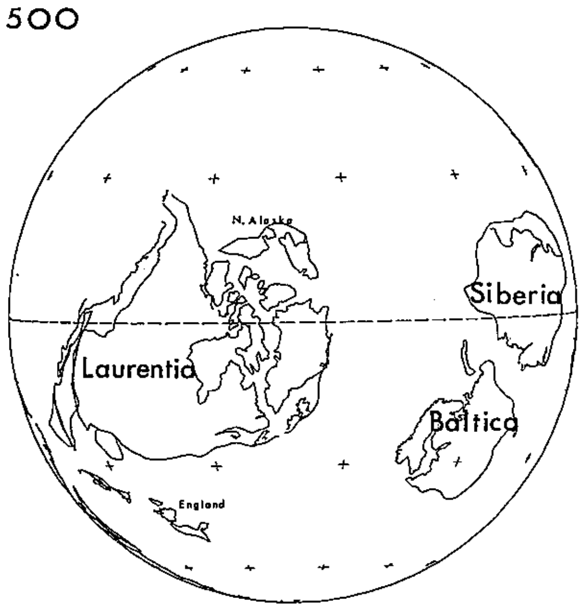

Fig. 1. Early Ordovician (500 million years ago).

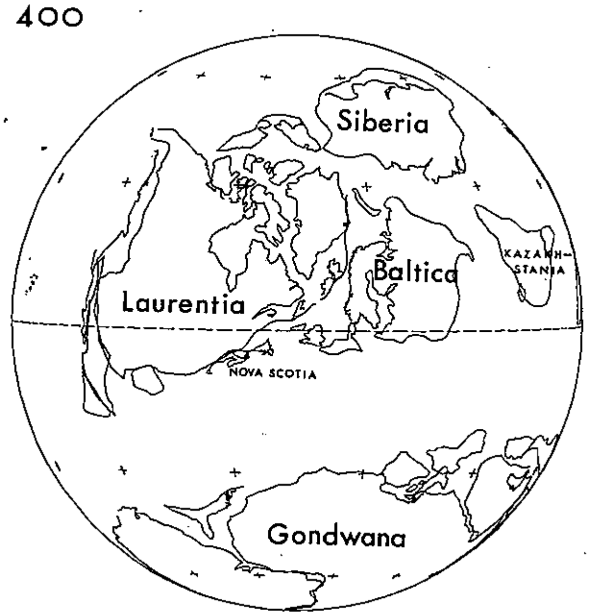

Fig. 2. Early Devonian (400 million years ago).

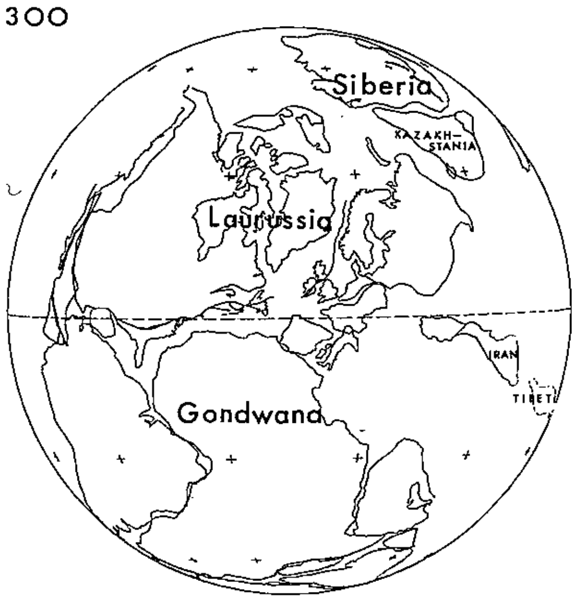

Fig. 3. Late Carboniferous (300 million years ago).

Reliable paleomagnetic data for the early Paleozoic are available from North America (Laurentia), Siberia, and Gondwana. Cambro-Ordovician data from Europe suggest that England and the Baltic shield were subtropical, while parts of southern and central Europe (Armorica) were associated with Gondwana near the South Pole (Hagstrum *et al.*, 1980). There is no paleomagnetic data from southeast Asia; however, broad carbonate platforms and faunal affinities indicate an equatorial association with Australia.

During the Middle Paleozoic the oceans separating these continents were subducted and the first of several continental collisions took place (Fig. 2). The Taconic, Caledonian, and Acadian orogenies have all been variously attributed to continent-continent collision (Bird and Dewey, 1970; McKerrow and Ziegler, 1972; Van der Voo, 1979). Though the timing of the collisions and the areas involved are disputed, all interpretations recognize that by the Middle Devonian Laurentia and Baltica had collided to form the 'Old Red continent'.

Recent paleomagnetic determinations from the Late Devonian of North America (Kent and Opdyke, 1978; Van der Voo, 1979) indicate that the arrangement of the continents after the collisions was not the same as the configuration at the time of breakup in the Jurassic. Baltica originally collided in a more southerly position relative to Laurentia (compare Figs. 2 and 3). This orientation was maintained from Late Silurian through Early Carboniferous (Kent, 1980; Kent and Opdyke, 1979).

Throughout the early and middle Paleozoic, Gondwana continued to move northward. The width of the ocean separating Gondwana from the northern continents is not known because there are few reliable paleomagnetic determinations from the southern continents of Siluro-Devonian age.

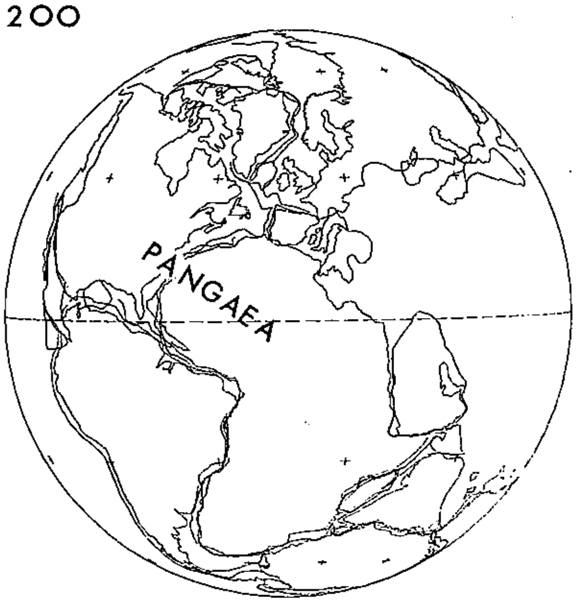

Fig. 4. Late Triassic (200 million years ago).

An alternate Devonian reconstruction has been proposed (HECKEL and WITZKE, 1979) which eliminates this southern ocean. In this interpretation, North America, Europe, and Siberia are displaced 30 degrees to the south so that they are adjacent to the northern coast of Africa. Though this 'Middle Paleozoic Pangaea' explains the distribution of a variety of climatic indicators and accounts for the observed similarity between North American and South American faunas it can not be reconciled with numerous late Devonian paleomagnetic determinations from North America and Siberia.

A single Silurian pole from China (KHRAMOV, 1975) places southeast Asia in equatorial latitudes during the Middle Paleozoic. A few determinations from the middle and late Devonian of Kazakhstan suggest that this area of southwestern U.S.S.R. occupied latitudes intermediate between Baltica and Siberia.

By the end of the Paleozoic the formation of Pangaea was nearly completed. Though numerous Permo-Carboniferous paleomagnetic determinations are available, there is considerable controversy regarding how this data should be used to reconstruct Pangaea.

Two versions of Pangaea have been proposed, Pangaea (A) and Pangaea (B). Pangaea (A) is the standard Wegnerian reconstruction (Fig. 4). Pangaea (B), in contrast, places North America against the northern coast of South America (IRVING, 1977). Irving suggests that Late Paleozoic paleomagnetic data require that the collision of the northern and southern continents resulted in the configuration, Pangaea (B). This relationship was maintained from early Carboniferous through early Triassic (IRVING, 1977). During the middle and late Triassic, Pangaea (B) was transformed to Pangaea (A) by means of strike slip motion between Gondwana and the northern continents. The concept of Pangaea (B) has yet to be critically tested using tectonic, geologic or paleogeographic data. A preliminary calculation of the rates of relative motion during the transition from Pangaea (B) to Pangaea (A) indicates that during the Triassic Gondwana moved past North America at a relatively rapid rate of 15 cm/year. An analysis of the distribution of Permian fusulinids suggests that the faunal provinces are better explained by Pangaea (A) (ROSS, 1979).

An alternate interpretation of late Permian and early Mesozoic paleomagnetic data does not require such drastic readjustments (VAN DER VOO and FRENCH, 1974; VAN DER VOO *et al.*, 1976). In the 'Van der Voo fit', North America is rotated tightly against northwest Africa, closing the Gulf of Mexico.

In the animation, Gondwana and the northern continents are shown shearing past one another during the early stages of collison. The Carboniferous is a time of intense tectonic activity both in Maritime Canada and Great Britain. Readjustments along the former Baltica-Laurentia collision zone took the form of left lateral transcurrent faulting which resulted in the opening of grabens in the Gulf of St. Lawrence and the North Sea. ARTHAUD and MATTE (1976) indicate that there is evidence of right lateral strike slip motion along the southern margin of the Baltic Shield which also may be associated with the collision of Gondwana.

5. The Mesozoic and Cenozoic

The Mesozoic and Cenozoic portions of the animation are based on recent plate tectonic models of the Atlantic (SCLATER *et al.*, 1977) and Indian oceans (NORTON and SCLATER, 1979). Paleomagnetic data from North America were used to orient the global reassemblies with respect to the pole (VAN ALSTINE and DE BOER, 1978).

In general, from Cretaceous through to the Recent, the plate motions shown in the film follow the outline of continental movements described by SMITH and BRIDEN (1977) in their set of Mesozoic and Cenozoic paleocontinental maps. The differences in the two models are reviewed elsewhere (SCOTESE, 1980). Prior to the Cretaceous, there are uncertainties regarding the early breakup history of the southern continents, and the tectonic histories of the Gulf of Mexico, Mediterranean, Arctic, and Antarctic regions.

The early spreading history of the Indian Ocean is not known, the there is still considerable debate as to how the eastern and western halves of Gondwana must be assembled. In Du Toit's original reconstruction of the southern continents, Madagascar was placed in the northern notch along the eastern coast of Africa, that is, adjacent to Kenya. Paleozoic paleomagnetic poles cluster most tightly when this fit is used (KLOOTWIJK, 1978). It has been proposed that the alternate fit of Madagascar adjacent to Mozambique results in a better alignment of the Tasman, Trans-Antarctic, and Cape fold belts (BARRON *et al.*, 1978).

A third reconstruction of the Indian Ocean (JOHNSON *et al.*, 1980), which though similar to Du Toit's fit, displaces India approximately 500 km to the south. This reconstruction matches Jurassic shorelines in Africa, Madagascar and India, and may better explain the pattern of magnetic anomalies in the Mozambique Basin. The reconstruction shown in the animation links the eastern and western halves of Gondwana together using a modified SMITH and HALLAM (1970) fit (Fig. 4).

The early tectonic history of the Gulf of Mexico is similarly constrained by the 'fit' used to reconstruct the surrounding continental blocks. The reconstruction used in the film requires that Mexico, Honduras, and the Yucatan peninsula be rotated to the

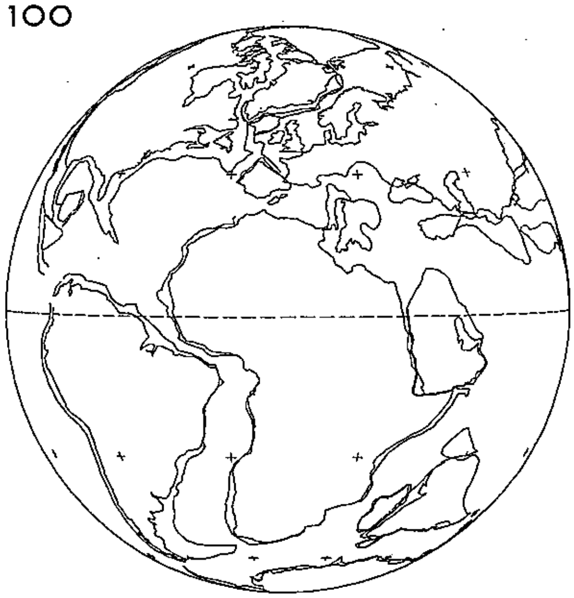

Fig. 5. Middle Cretaceous (100 million years ago).

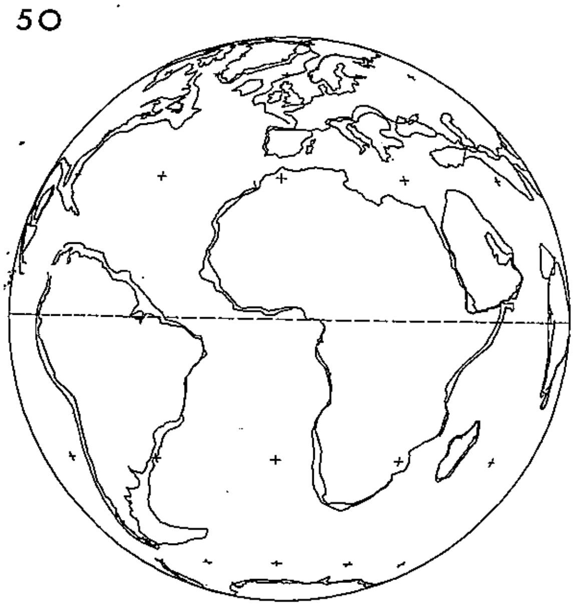

Fig. 6. Eocene (50 million years ago).

northwest and out of the way of South America. There is some evidence for major sinistral faults in Mexico and southwestern United States along which this motion may have taken place (Silver and Anderson, 1974; McKee and Jones, 1979). Other reconstructions of the Gulf of Mexico displace Mexico and Central America in a similar manner (Pilger, 1978).

The tectonic histories of the Arctic and Antarctic regions must remain speculative at this time. Paleomagnetic evidence may support a counterclockwise rotation of the northern peninsula of Alaska away from Arctic Canada (Sweeney *et al.*, 1978). The timing of this rotation is not documented, but it may have coincided with some of the thrusting in the Brooks Range (Tailleur and Snelson, 1969). Portions of eastern Siberia must also be included with this northern Alaskan block, however, it is not clear where the western suture lies.

Western Antarctica is probably composed of several microcontinents. In addition to the Western Antarctic peninsula, the Ellsworth mountains and Marie Byrdland must be accounted for in any reconstruction of the southern oceans. The reassembly shown in the film is similar to the reconstruction of De Wit (1977). Marie Byrdland is collapsed against East Antarctica, and the Ellsworth mountains are rotated clockwise so that the folded Paleozoic terrains line up with the main trend of the Trans-Antarctic mountains. The Western Antarctic peninsula is fitted against the Falkland plateau, providing a southern continuation of the Andean Cordillera. An alternate reconstruction based on paleomagnetic data (Alley and Watts, 1979) rotates the peninsula clockwise against eastern Antarctica, closing the Weddell Sea.

6. Conclusion

The computer animation described in this article allows the viewer to evaluate the dynamic and temporal aspects of continental motions. The film is naturally limited by the decreasing quality of geologic information the further one goes back in time. It is planned that as new data becomes available, and as new technology develops, we will be able to make improvements in the animation.

REFERENCES

Alley, R. and D. R. Watts, Paleomagnetic investigation of the northern peninsula, *EOS, Trans. Am. Geophys. Union*, **60**, 240, 1979.

Arthaud, F. and P. Matte, Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Results of the right-lateral shear zone between the Appalachians and the Urals, *Geol. Soc. Am. Bull.*, **88**, 1305–1320, 1977.

Bambach, R. K., C. R. Scotese, and A. M. Ziegler, Before Pangea: the geography of the Paleozoic world, *Am. Scientist*, **68**, 26–38, 1980.

Barron, E. J., C. G. A. Harrison, and W. W. Hay, A revised reconstruction of the southern continents, *EOS, Trans. Am. Geophys. Union*, **59**, 436–449, 1978.

Bird, J. M. and J. F. Dewey, Lithosphere plate: Continental margin tectonics and the evolution of the Appalachian orogen, *Geol. Soc. Am. Bull.*, **81**, 1031–1059, 1970.

De Wit, M. J., The evolution of the Scotia Arc as a key to the reconstruction of southwestern Gondwanaland, *Tectonophys.*, **37**, 53–81, 1977.

HAGSTRUM, J. T., R. VAN DER VOO, B. AUVRAY, and N. BONHOMMET, Eocambrian-Cambrian palaeomagnetism of the Armorican massif, France, *Geophys. J. R. Astr. Soc.*, **60**, 489–517, 1980.

HECKEL, P. H. and B. J. WITZKE, Devonian world paleogeography determined from the distribution of carbonates and related lithological paleoclimatic indicators, Special Papers in Palaeontol., No. 23, pp. 99–123, 1979.

IRVING, E., Drift of the major continental blocks since the Devonian, *Nature*, **270**, 304–309, 1977.

JOHNSON, B. D., C. MCA. POWELL, and J. J. VEEVERS, Early spreading history of the Indian Ocean between India and Australia. Earth Plan, *Sci. Lett.*, 1980 (in press).

KANASEWICH, E. R., J. HAVSKOV, and M. E. EVANS, Plate tectonics in the Phanerozoic, *Can. J. Earth Sci.*, **15**, 919–955, 1978.

KENT, D. V., The formation of Euramerica in the Paleozoic, *EOS, Trans. Am. Geophys. Union*, **61**, 220–221, 1980.

KENT, D. V. and N. D. OPDYKE, Paleomagnetism of the Devonian Catskill red beds: evidence for motion of coastal New England—Canadian maritime region relative to cratonic North America, *J. Geophys. Res.*, **83**, 4441–4450, 1978.

KENT, D. V. and N. D. OPDYKE, Further evidence for the early Carboniferous field of North America and its bearing on Carboniferous tectonics of the northern Appalachians, *Earth Planet. Sci. Lett.*, **44**, 365–372, 1979.

KLOOTWIJK, C. T., A review of paleomagnetic data from the Indo-Pakistani fragment of Gondwanaland, in *Geodynamics of Pakistan*, edited by A. Favah and K. A. DeJong, pp. 41–80, Pakistan Geol. Survey Pub., 1978.

KHRAMOV, A. N., Palaeomagnetic directions and paleomagnetic poles, Data for U.S.S.R., in *Materials for World Data Center B*, Vol. 3, Soviet Geophysical Committee of the Academy of Sciences of the U.S.S.R., 1975.

MCKEE, J. W. and N. W. JONES, A large Mesozoic fault in Coahuila, Mexico, Geol. Soc. Am., Abstracts with programs, Vol. 11, p. 476, 1979.

MCKERROW, W. S. and A. M. ZIEGLER, Palaeozoic Oceans, *Nature*, **240**, 92–94, 1972.

MOREL, P. and E. IRVING, Tentative paleocontinental maps for the early Phanerozoic and Proterozoic, *J. Geol.*, **86**, 535–561, 1978.

NORTON, I.O. and J. G. SCLATER, A model for the evolution of the Indian Ocean and the breakup of Gondwanaland, *J. Geophys. Res.*, **84**, 6803–6830, 1979.

PILGER, R. H., A closed Gulf of Mexico, pre-Atlantic Ocean plate reconstruction and the early rifting history of the Gulf of Mexico and the North Atlantic, *Trans. Gulf Coast Assoc.*, **28**, 385–393, 1978.

ROSS, C. A., Late Paleozoic collision of North and South America, *Geology*, **7**, 41–44, 1979.

SCLATER, J. G., S. HELLINGER, C. TAPSCOTT, The paleobathymetry of the Atlantic Ocean from the Jurassic to the present, *J. Geol.*, **85**, 509–552, 1977.

SCOTESE, C. R. and D. W. BAKER, Continental drift reconstructions and animation, *J. Geol. Educ.*, **23**, 167–171, 1975.

SCOTESE, C. R., R. K. BAMBACH, C. BARTON, R. VAN DER VOO, and A. M. ZIEGLER, Paleozoic base maps, *J. Geol.*, **87**, 217–277, 1979.

SCOTESE, C. R., A review of Mesozoic and Cenozoic Paleocontinental Maps, by A. G. Smith and J. C. Briden, New York, 1977 (Cambridge Univ. Press), *Am. J. Sci.*, **280**, 93–96, 1980.

SILVER, L. T. and T. H. ANDERSON, Possible left-lateral early to middle Mesozoic disruption of the southwestern North American craton, Geol. Soc. Am., Abstracts with programs, Vol. 6, p. 955, 1974.

SMITH, A. G., J. C. BRIDEN, and G. E. DREWRY, Phanerozoic world maps, in *Organisms and Continents Through Time*, Palaeontol. Assoc. Spec. Pap., **12**, 1–42, 1973.

SMITH, A. G. and J. C. BRIDEN, *Mesozoic and Cenozoic Paleocontinental Maps*, 63 pp., Cambridge Univ. Press, New York, 1977.

SMITH, A. G. and A. HALLAM, The fit of the southern continents, *Nature*, **225**, 139–144, 1970.

SWEENEY, J. F., E. IRVING, and J. W. GEUER, Evolution of the Arctic Basin, in *Arctic Geophysical Review*, Vol. 45, edited by J. F. Sweeney, pp. 91–100, Pub. Earth Physics Branch, Ottawa, Canada, 1978.

TAILLEUR, I. L. and S. SNELSON, Large scale thrusting in northwestern Alaska possibly related to rifting of the

Arctic Ocean. (abs)., Geol. Soc. Am. Spec. Pap., **121**, p. 569, 1969.

VAN ALSTINE, D. R. and J. DE BOER, A new technique for constructing apparent polar wander paths and the revised Phanerozoic path for North America, *Geology*, **6**, 137–139, 1978.

VAN DER VOO, R. and R. B. FRENCH, Apparent polar wandering for the Atlantic bordering continents: Late Carboniferous to Eocene, *Earth Sci. Rev.*, **10**, 99–119, 1974.

VAN DER VOO, R., F. J. MAUK, and R. B. FRENCH, Permian—Triassic continental configuration and the origin of the Gulf of Mexico, *Geology*, **4**, 177–180, 1976.

VAN DER VOO, R., A. N. FRENCH, and R. B. FRENCH, A paleomagnetic pole position from the folded late Devonian catskill redbeds, and its megatectonic implications, *Geology*, **7**, 345–348, 1979.

VAN DER VOO, R., Paleozoic assembly of Pangaea: a new model for the Taconic Caledonian, and Hercynian orogenies, *EOS, Trans. Am. Geophys. Union*, **6**, 241, 1979.

ZIEGLER, A. M., C. R. SCOTESE, W. S. MCKERROW, M. E. JOHNSON, and R. K. BAMBACH, Paleozoic Paleogeography, *Ann. Rev. Earth Planet. Sci.*, **7**, 473–502, 1979.

ZIEGLER, A. M., C. R., SCOTESE, W. S. MCKERROW, M. E. JOHNSON, and R. K. BAMBACH, Paleozoic biogeography of the continents bordering the Iapetus (pre-Caledonian) and Rheic (pre-Hercynian) Oceans, in *Paleontology and Plate Tectonics, Special Pub. in Bio. and Geo.*, No. 2, pp. 1–34, Milwaukee Public Museum, 1977.

ZONENSHAYN, L. P. and A. M. GORODNITSKIY, Paleozoic and Mesozoic reconstructions of the continents and oceans, Article 1.—Early and Middle Paleozoic reconstructions, *Geotectonics*, **11**, 83–94, 1977a.

ZONENSHAYN, L. P. and A. M. GORODNITSKIY, Paleo-Mesozoic and Mesozoic reconstructions of the continents and oceans, Article 2.—Late Paleozoic and Mesozoic reconstructions, *Geotectonics*, **11**, 159–172, 1977b.