CONTINENTAL DRIFT

Christopher R. Scotese
PALEOMAP Project

These maps illustrate the movements of the continents during the last 750 million years. All age assignments are based on the 1999 DNAG timescale. This flipbook is dedicated to the memory of W. Stuart McKerrow, without whose help, collaboration, advice, support, encouragement and guidance through the years, none of the work of the PALEOMAP Project would have been possible.

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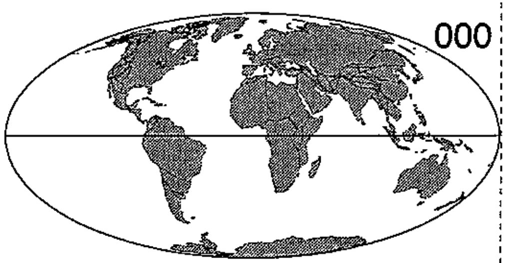

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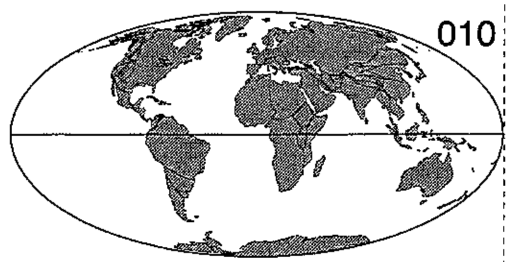

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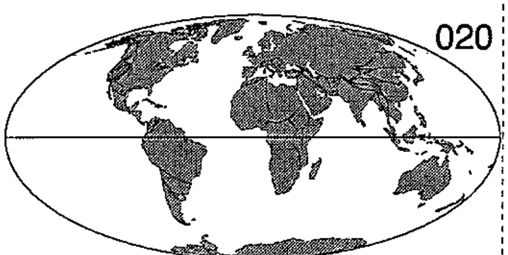

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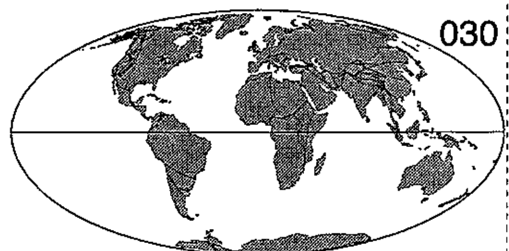

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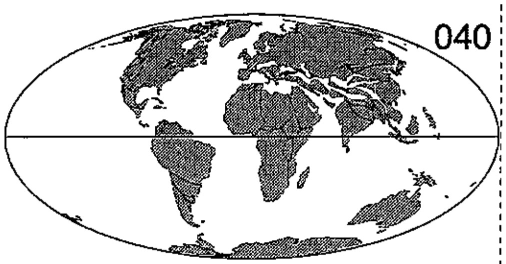

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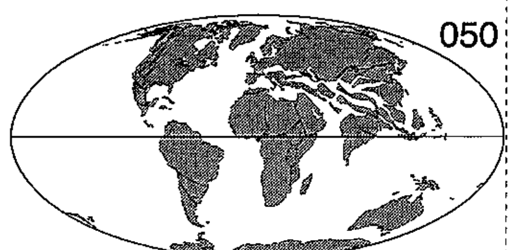

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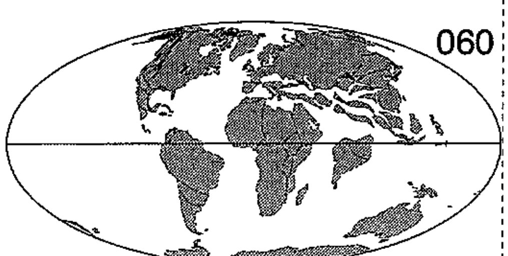

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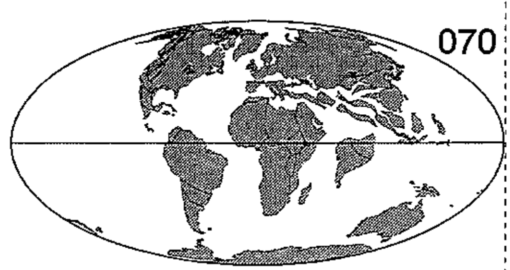

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A Continental Drift Flipbook

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ABSTRACT

Forty-six miniature plate tectonic reconstructions are presented that can be assembled into a "flipbook" that illustrates the movement of the continents since the Late Precambrian, 750 m.yr. ago. Six principal lines of evidence have been used to reconstruct the past positions of the continents: (1) linear magnetic anomalies produced by sea floor spreading, (2) paleomagnetism, (3) hotspot tracks and large igneous provinces, (4) the tectonic fabric of the ocean floor mapped by satellite altimetry, (5) lithologic indicators of climate (e.g., coals, salt deposits, tillites), and (6) the geologic record of plate tectonic history. I discuss the probable uncertainties associated with the plate tectonic reconstructions and give an estimate of the uncertainty in the positions of the continents back through time.

Introduction

In 1973, while an undergraduate at the University of Illinois in Chicago, I produced the first continental drift "flipbook" (Scotese 1975, 1976; Scotese and Baker 1975). In the same year, I met W. S. McKerrow, from Oxford University, who was visiting Professor A. M. Ziegler at the University of Chicago. Professor McKerrow had come to the University of Illinois to give a lecture on a new set of Phanerozoic plate tectonic reconstructions by Smith, Briden, and Drewry that was soon to be published by the Palaeontological Association (Smith et al. 1973). This chance meeting inspired me to try to make better plate tectonic reconstructions, to produce a new version of the continental drift flipbook, and to produce computer animations showing the history of plate motions. Later that spring, while working as a volunteer at the Field Museum of Natural History, I met G. Forney, one of Professor Ziegler's graduate students, and I gave him a revised continental drift flipbook. Soon after that, I was invited to give a talk describing my research to Professor Ziegler and his students in the Department of Geophysical Sciences, and as they say, "the rest is history."

Through the years, numerous editions of the continental drift flipbook have been produced, ranging in size from the first thumb-sized edition to later pocket-sized versions. The various editions of the continental drift flipbook now reside in desk drawers and in the dusty corners of bookcases across the globe. The present maps are a reprint of the seventh edition of the continental drift flipbook (Scotese 1997).

The maps that comprise this flipbook are the result of more than 25 yr of plate tectonic model building and data synthesis (Scotese and Baker 1975; Scotese et al. 1979, 1981, 1988; Ziegler et al. 1983; Scotese and Sager 1988; Scotese and Golonka 1992; Jurdy et al. 1995). These plate tectonic reconstructions have been used by numerous authors to illustrate paleogeographic (Ronov et al. 1984, 1989; Ziegler 1989; Cook 1990; Kazmin and Natopov 1998; Golonka 2000; Scotese 2001; Blakey 2003), paleoclimatic (Otto-Bliesner et al. 1994; Golonka et al. 1996; A. J. Boucot, C. Xu, and C. R. Scotese, unpub. manuscript), and biogeographic change (McKerrow and Scotese 1990; Cocks and Scotese 1991; Chatterjee and Scotese 1999). The plate tectonic reconstructions of the PALEOMAP Project are similar to other compilations (Zonenshain et al. 1990; Dercourt et al. 1993; Smith et al. 1994; Hay et al. 1999; Vrielynck and Bouyesse 2001) because similar geophysical data sets have been used by these research group to construct the maps.

The 46 miniature plate tectonic reconstructions that make up the continental drift flipbook illus-

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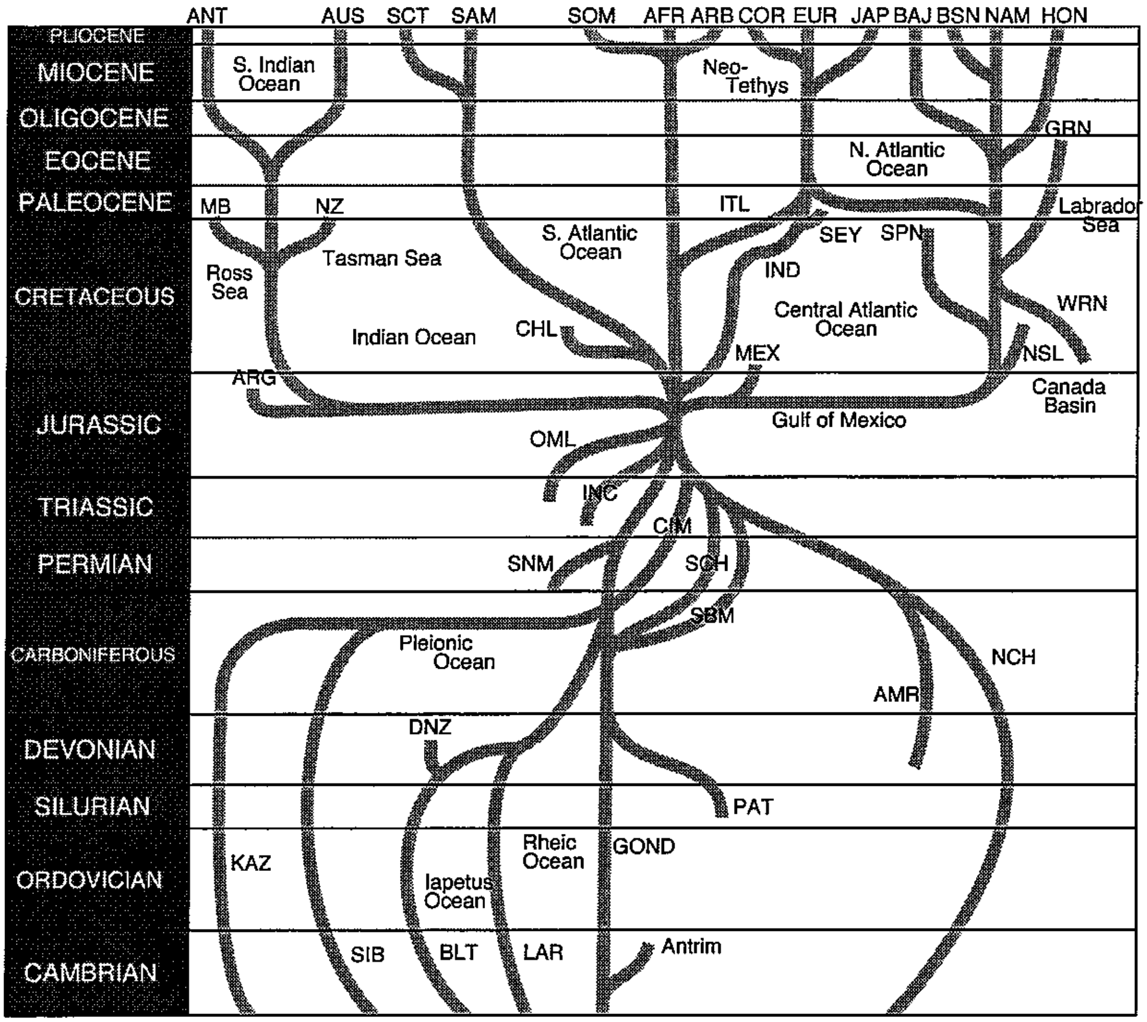

AFR = Africa; AMR = Amuria; ANT = Antarctica; ARB = Arabia; ARG = Argoland; AUS = Australia; BAJ = Baja California; BLT = Baltica; BSN = Basin and Range; CHL = Chile; CIM = Cimmeria; COR = Corsica and Sandinia; DNZ = Donetz Basin; EUR = Europe; GOND = Gondwana; GRN = Greenland; HON = Honduras; INC = Indochina; IND = India; ITL = Italy; JAP = Japan; KAZ = Kazkhstan; LAR = Laurentia; MEX = Mexico; MB = Marie Byrdland; NAM= North America; NCH = North China; NSL = North Slope of Alaska; NZ = New Zealand; OML = Omolon; PAT = Patagonia; SAM = South America; SBM = Sibumasu; SCH = South China; SCT = Scotia Arc; SEY = Seychelles SIB = Siberia; SNM = Sonomia; SOM - Somalia; SPN = Spain; WRN = Wrangellia

Figure 1. Plate tectonic tree diagram. Branching events represent the breakup of continents and the formation of a new ocean basin. "Roots" are continental collisions. A branch that terminates represents an ocean basin that has stopped opening.

trate the movement of the continents since the Late Precambrian, 750 m.yr. ago. The maps have been laid out so that a reader can copy the pages from the journal, cut out the maps along the dotted lines, and assemble the maps into a flipbook. By flipping through the pages of the continental drift flipbook, the movements of the continents can be easily animated. It is well known that the positions of the continents and the sizes and shapes of the ocean basins are continually changing as a result of plate tectonics. The term "continental drift" rather than "plate tectonics" was used to describe the flipbook because these maps illustrate only the movement of the continents. Mid-ocean ridges, subduction zones, and other plate tectonic features, though implicit, are not shown. The shaded areas

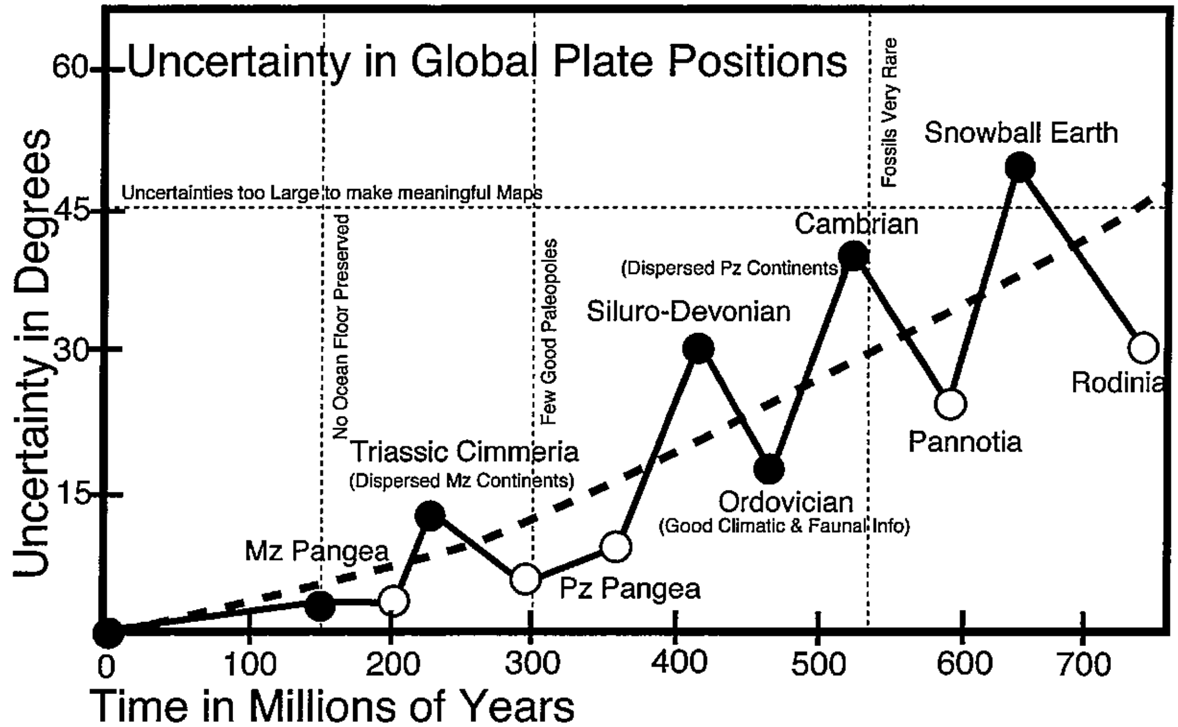

Figure 2. Estimates of uncertainty in plate position

represent the approximate extent of continental lithosphere. Modern coastlines are shown rather than paleo-coastlines so that the modern continents and continental fragments can be more easily recognized. Also it should be noted that the gaps that sometimes appear between the continental fragments, for example, along the trend of the Rocky Mountains, are artifacts of the reconstruction method and do not represent seaways. Like an "exploded" mechanical diagram, these gaps indicate that compressive deformation has occurred in these regions. In these cases, the gaps are a crude attempt at palinspastic restoration. (For additional instructions describing how to assemble the flipbook, see the legend for fig. 3.)

These maps encapsulate a vast amount of geological time and condense 750 m.yr. of plate motions into a few seconds of "flipping." For more information about the geological, paleontological, paleoclimatic, and tectonic events that took place during the time interval, see the PALEOMAP Project Web site, http://www.scotese.com, and a companion article describing plate tectonic and paleogeographic events since the Triassic (Scotese 2004). Copies of figure 3 have been posted at the PALEOMAP Project Web site for convenient downloading. It is now also possible to produce plate tectonic reconstructions online via the Web. The following Web sites allow users to produce and download customized plate tectonic reconstructions: http://www.odsn.de/odsn/services/paleomap/paleomap.html and http://www.itis-molinari.mi.it/intro-reconstr.html.

Mapping the Past Positions of the Continents

The motions of the continents shown in the continental drift flipbook are summarized in figure 1. Across the top, arrayed horizontally, are abbreviations signifying the modern continents. The "branches" that represent each modern continent can be traced downward across the diagram and backward through time. For instance, though South America (fig. 1, *SAM*) and Africa (fig. 1, *AFR*) now are separate continents, if we follow their branches backward through time, we see that they come together in the Early Cretaceous. The opening of the South Atlantic Ocean coincides with the split of the South American and African continental branches.

The most striking feature of the plate tectonic tree diagram is the constricted waistline that spans the Triassic and Early Jurassic time interval. The convergence of all the branches back to a single "trunk" signifies that all land areas were joined together in one supersized landmass. This supercontinent is known as "Pangea" (Wegener 1912). Before the time of Pangea, the world's continents were dispersed, much like today's world. However, there is a hint that the roots of the plate tectonic tree converge yet again, in the Late Precambrian. This Late Precambrian supercontinent is poorly known and goes by the names "greater Gondwana," Pannotia, or Rodinia (Dalziel 1991, 1997; Hoffman 1991; Moores 1991; Powell et al. 1993; Meert and Van der Voo 1994).

The plate tectonic history of the continents and ocean basins during the past 750 m.yr. is reconstructed using the following six lines of evidence: (1) linear magnetic anomalies produced by sea floor spreading, (2) paleomagnetism, (3) hotspot tracks and large igneous provinces (LIPs), (4) the tectonic fabric of the ocean floor mapped by satellite altimetry, (5) lithologic indicators of climate (e.g., coals, salt deposits, tillites), and (6) the geologic record of plate tectonic history.

Linear Magnetic Anomalies Produced by Sea Floor Spreading. Like the sun's magnetic field, the earth's magnetic field "flips," or reverses polarity. As new ocean floor cools at mid-ocean ridges, it is magnetized in the direction of the prevailing magnetic polarity (normal or reverse). Fluctuations, or "anomalies," in the intensity of the magnetic field occur at the boundaries between normally magnetized sea floor and portions of the sea floor that were magnetized in the reverse direction. The age and duration of these linear magnetic anomalies can be determined using fossil evidence from the sea floor and radiometric techniques. Because these magnetic anomalies form at the mid-ocean ridges, they tend to be long, linear features (hence the name "linear magnetic anomalies") that are symmetrically arranged about the mid-oceanic ridges axes. The positions of the continents during the past 150 m.yr. can be directly reconstructed by superimposing linear magnetic anomalies of the same age from opposite sides of an ocean basin.

During the decades between 1965 and 1995, the pattern of linear magnetic anomalies in 80% of the world's ocean basins was mapped by marine geophysical surveys. These data were initially synthesized and summarized by the PALEOMAP Project and were ultimately used to produce a detailed map of the age of the ocean basins (Mueller et al. 1996). For an ocean-by-ocean summary of the plate tectonic development of the world's ocean basin, see the study by Scotese and Sager (1988).

Paleomagnetism. By measuring the remanent magnetic field often preserved in iron-bearing minerals in rock formations, paleomagnetic analysis can determine whether a rock was magnetized near the North or South Pole or near the equator. Thus, paleomagnetism provides direct evidence of a continent's north-south (latitudinal) position but does not constrain its east-west (longitudinal) position.

The paleomagnetic data used in this chapter to reposition the continents were compiled by Van der Voo (1993) and reevaluated in light of the PALEOMAP plate tectonic model by Bocharova and Scotese (1993). For recent summaries of paleomagnetic data and procedures, see studies by McElhinny and McFadden (1998) and A. Schettino and C. R. Scotese (unpub. data).

Hotspot Tracks and LIPs. Plate tectonics is a description of the movement of the lithosphere, the rigid, outermost layer of the earth. Most volcanic eruptions are derived from magmas that have their source within the lithosphere; however, a significant subset, hotspot volcanics, are derived from much deeper magma sources. Some of these deep sources of magma may originate near the boundary between the earth's liquid core and lower mantle and ascend to the surface in mantle plumes or hotspots (Duncan 1981; Morgan 1981; Duncan and Richards 1991).

Hotspots literally burn through the lithosphere and erupt at the surface forming large, but rarely explosive, volcanoes (e.g., Mauna Loa). When a hotspot plume first breaks through to the surface, the large volume of magma in the plume head can spread across a continent as a flood basalt or LIP

Figure 3. Continental drift flipbook (Scotese 1997). The number in the upper right-hand corner is the age in millions of years according to the 1999 Decade of North American Geology timescale. The name of the geological interval appears in the lower right-hand corner at the start of each sequence. To assemble the continental drift flipbook, copy these pages onto a heavy weight paper or card stock. Cut out the individual maps along the dotted lines. Arrange the maps in order, either with time ascending or with time descending. Insert the optional "sound effects" cards at the desired locations. Hold the assembled booklet firmly between thumb and index finger and tap the right-hand edge sharply on a hard, flat surface. Staple the left-hand margin approximately one-quarter inch from the edge. To "flip" the continental drift flipbook, hold stapled margin in left hand and flip the pages between the thumb and index finger of the right hand.

CONTINENTAL DRIFT

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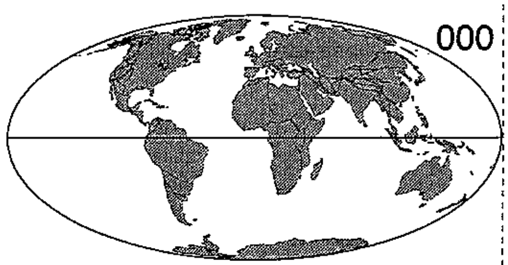
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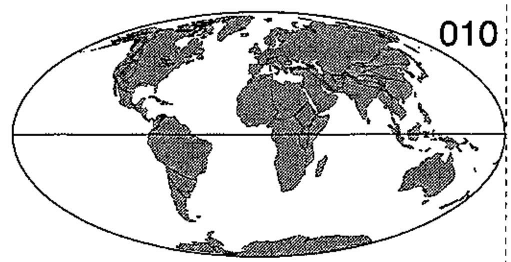
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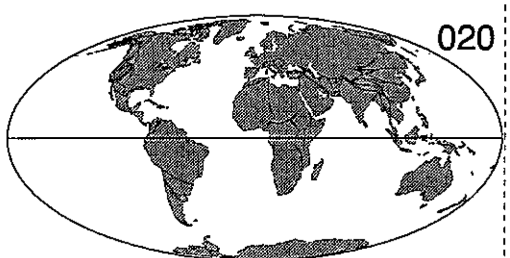
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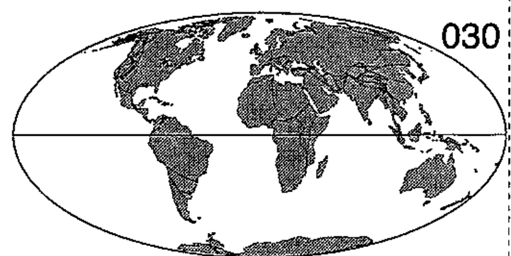
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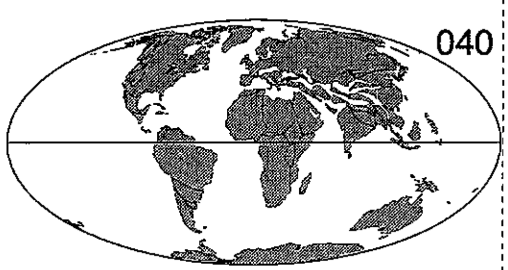
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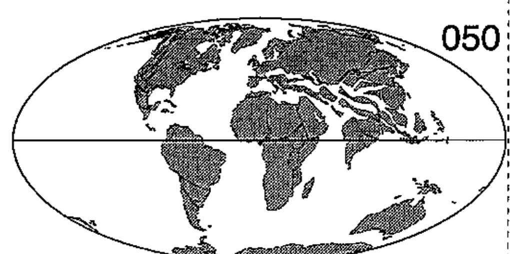
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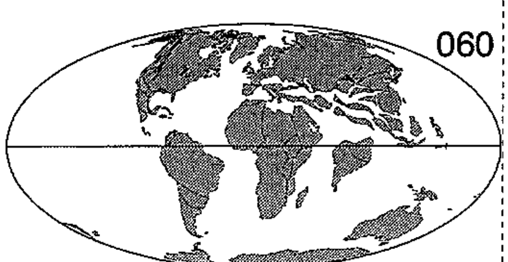
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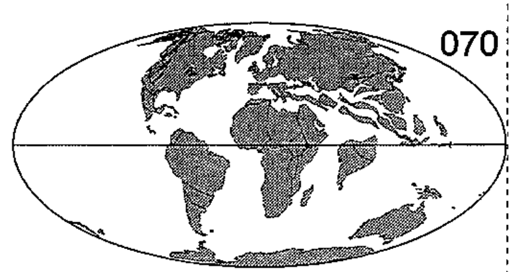
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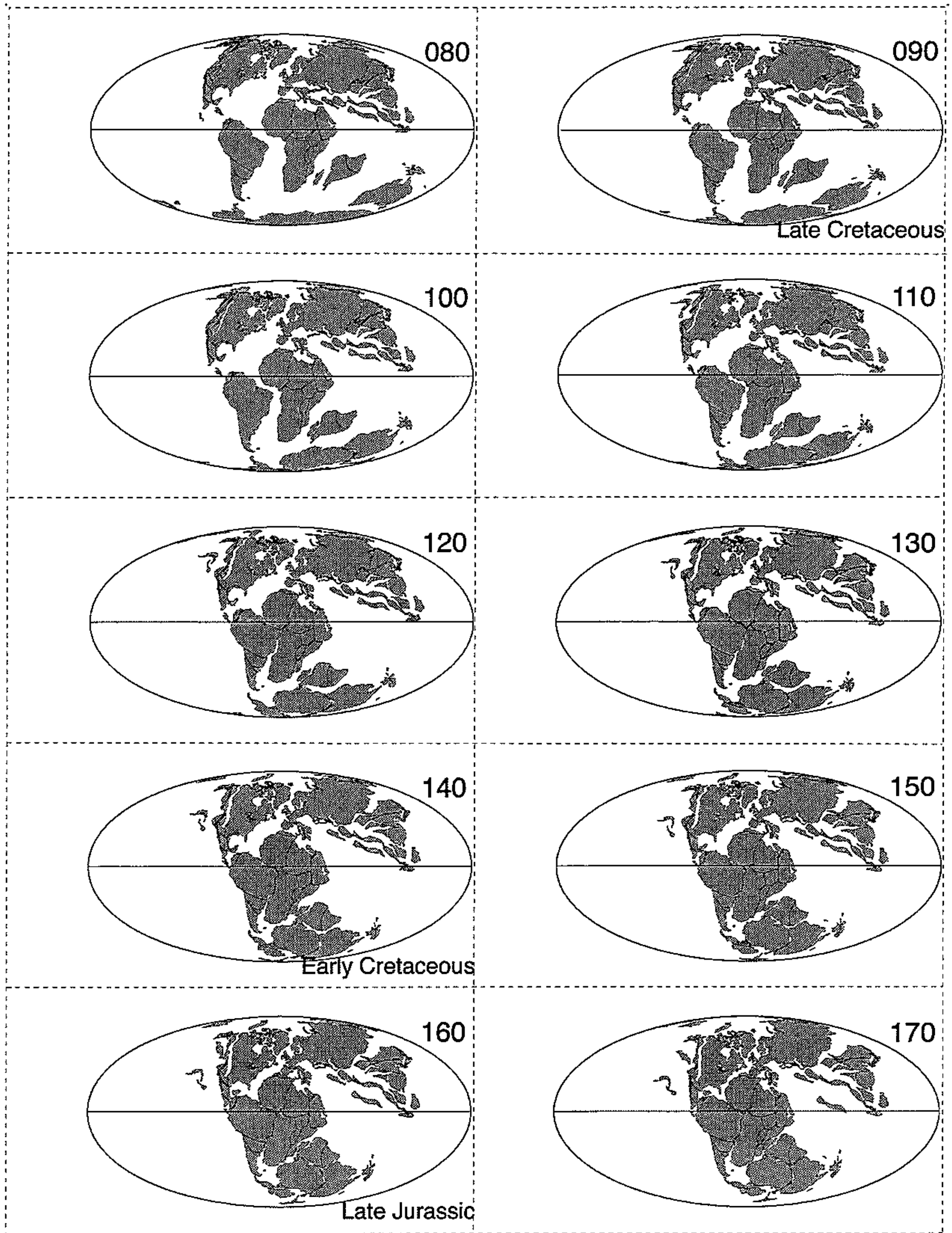

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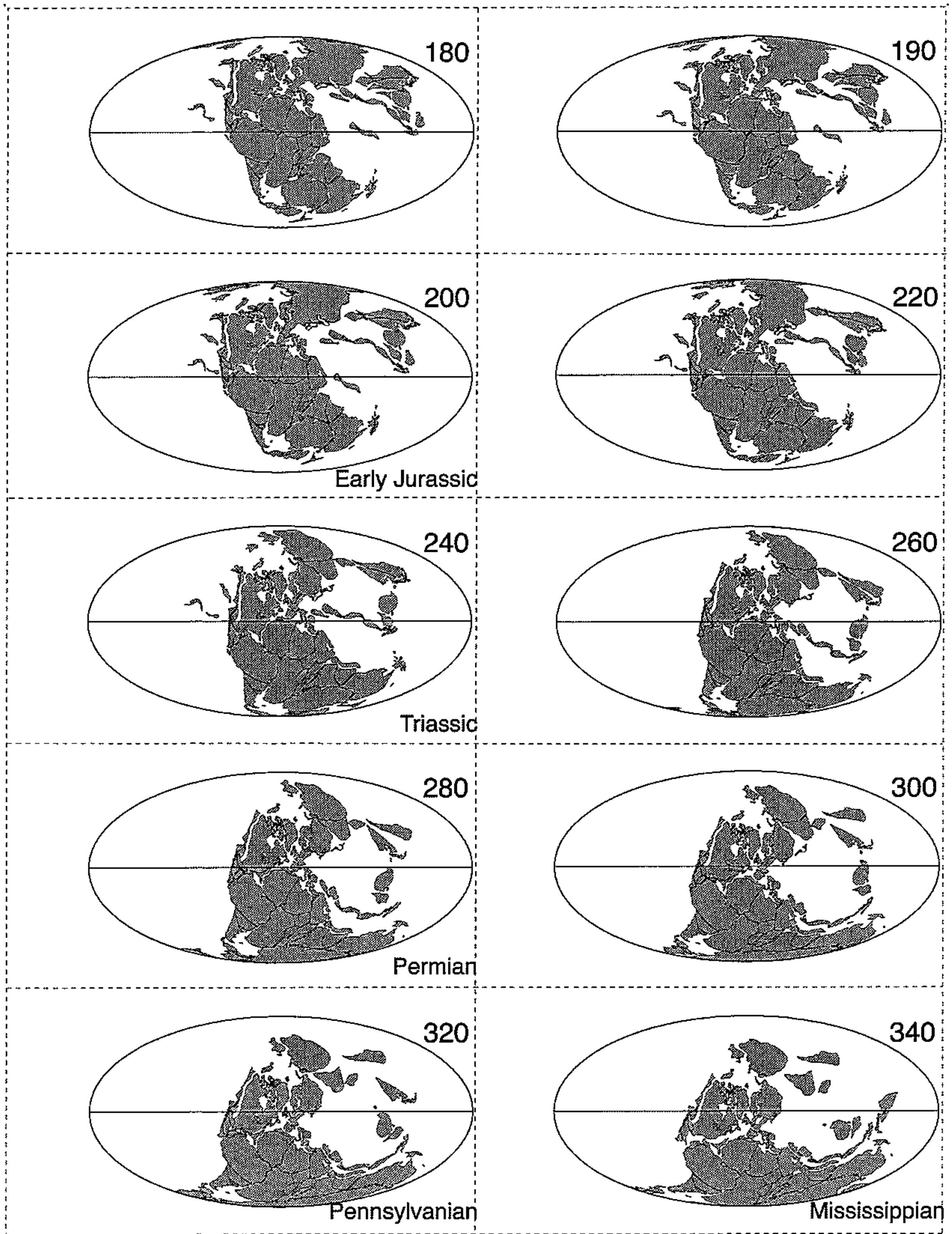

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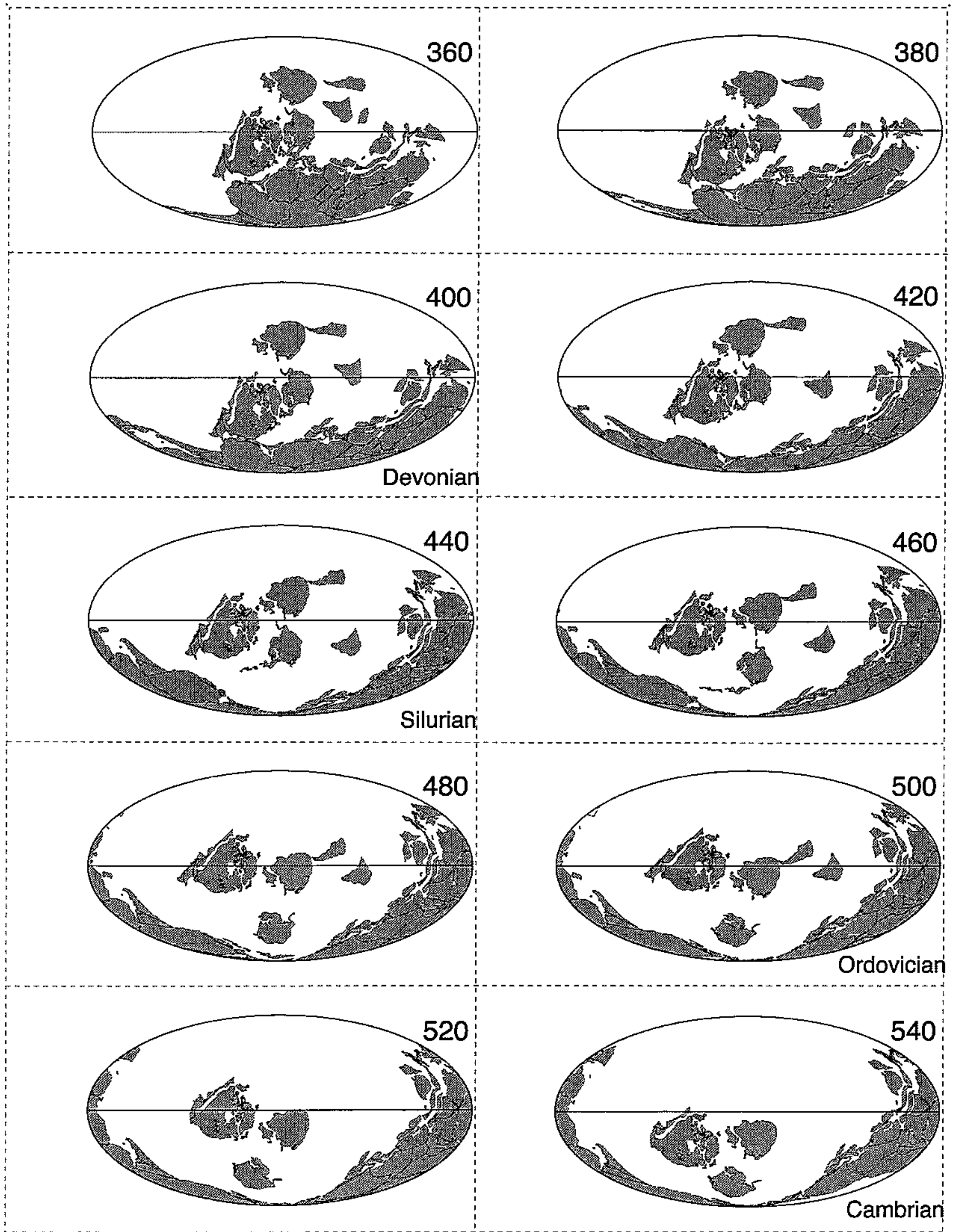

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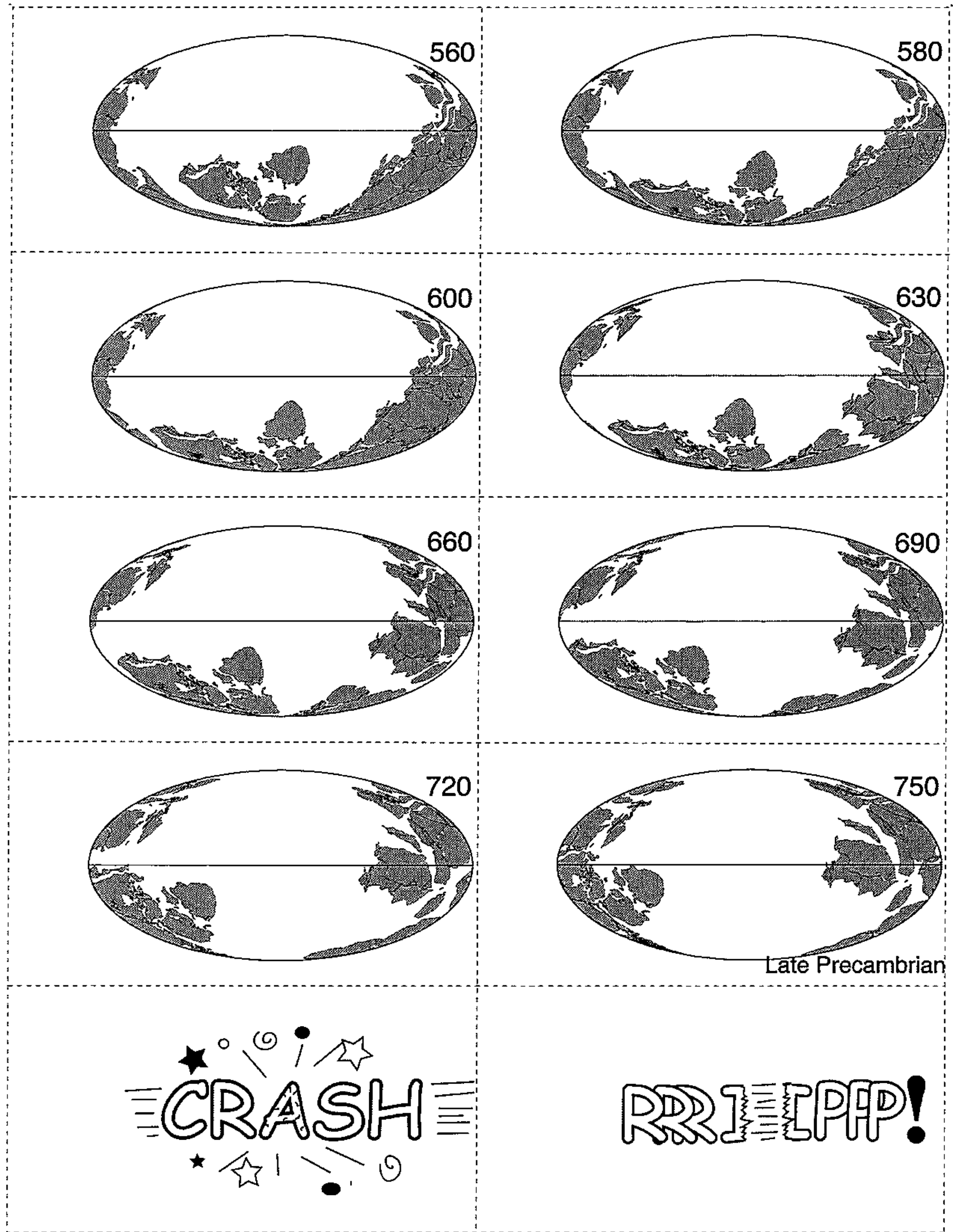

Figure 3. *(Continued)*

(Mahoney and Coffin 1997; Eldholm and Coffin 2000). As a plate moves over the more or less stationary hotspot, a sequential chain of volcanic islands, or hotspot track, is formed. The Hawaiian Islands and Emperor seamount chain were formed in this manner (Wilson 1963).

Hotspots are very useful in reconstructing past plate motions because (1) they date the start of continental rifting and sea floor spreading and (2) hotspot tracks provide an independent estimate of both north-south and east-west plate motion (Mueller et al. 1993). Hotspots appear to be relatively stationary for long periods of time, and in only a few cases has significant motion of hotspots been documented (Norton 1995, 2000).

Tectonic Fabric of the Ocean Floor Mapped by Satellite Altimetry. Satellites equipped with radar altimeters can precisely measure the distance from an orbiting satellite to the earth's surface. These distance measurements can be used to create detailed, digital topographic and bathymetric maps. The pioneering work of Haxby (1987) together with the more recent digital maps of Smith and Sandwell (1997) have mapped out the location of mid-ocean ridges, oceanic fracture zones, volcanic seamounts, extinct spreading ridges, deep-sea trenches, and submarine plateaus.

Information from satellite altimetry has played a critical role in the plate tectonic reconstruction of ocean basins (Gahagan et al. 1988). The long, linear fracture zones defined by this method can be used to progressively guide the continents back together (Reeves and de Wit 2000). The past spreading history of the ocean basins can be mapped and extinct spreading centers located. From the pattern and distribution of seamounts and hotspot tracks, the relative motion between the plates and the earth's interior can be deduced.

Lithologic Indicators of Climate. The earth's climate is primarily a result of the redistribution of the sun's energy across the surface of the globe. It is warm near the equator and cool near the poles. Wetness, or rainfall, also varies systematically from the equator to the pole. It is usually wet near the equator, dry in the subtropics, wet in the temperate belts, and dry near the poles.

Certain kinds of rocks form under specific climatic conditions. For example, coals occur where it is wet, bauxite occurs where it is warm and wet, evaporites and calcretes occur where it is warm and dry, and tillites occur where it is wet and cool (Parrish et al. 1982; Scotese and Barrett 1990; Parrish 1998; Ziegler et al. 2003; A. J. Boucot, C. Xu, and C. R. Scotese, unpub. manuscript). The ancient distribution of these rock types can tell us how global climate has changed through time (Ice House vs. Hot House) and provide an independent estimate of the north-south position of a continent (paleolatitude).

Geologic Record of Plate Tectonic History. Finally, the best source of information, but often the most difficult to interpret, is the geologic record left by plate tectonic activity. The rock record has information about environments of deposition (deep sea, shallow sea, lowlands, and uplands), as well as the history of plate tectonic activity (faults, folding, thrusting, and rifting).

During the past 250 yr, geologists have mapped out the age, environment of deposition, and tectonic history of the rocks at the earth's surface. This knowledge of the regional tectonics and geology allows us to map the ancient sites of rifting, subduction, continental collision, and other important plate tectonic events.

Estimating Uncertainties in the Past Positions of the Continents

The plate tectonic maps presented here are visual hypotheses that seek to explain incomplete and sometimes contradictory observations. It is, therefore, reasonable to ask the question, How accurate are the positions of the continents shown on these maps? The techniques described in the previous section often have statistical methods for measuring error and estimating uncertainty. For example, in paleomagnetic studies, individual paleomagnetic poles are often combined into mean, or averaged, paleopole positions. These averages include estimates of precision (α_{95}) and dispersion (k; Van der Voo 1993; McElhinny and McFadden 1998). Similar statistics can be used to evaluate how well lithologic indicators of climate match the paleolatitudes predicted by a given plate reconstruction (Scotese and Barrett 1990). Likewise, the goodness of fit between matching magnetic anomalies, or the trend of a hotspot track with the trajectory of plate motion, can also be calculated. However, there is no simple or direct way to summarize all these estimates of uncertainty into a single, meaningful, quantitative estimate of error.

Despite this problem, it is still worthwhile to discuss the probable uncertainties associated with the plate tectonic reconstructions. Figure 2 provides an estimate of the uncertainty in the positions of the continents back through time. This figure also indicates some of the criteria used to estimate these uncertainties. In figure 2, geological time lies along the horizontal axis. The uncertainty in the position of the continents is expressed in terms of degrees of latitude (vertical axis). For instance, the left-hand side of the graph starts at time 0 (0 m.yr.), with 0° of uncertainty. (We know exactly where the continents are today.) As we scan to the right, going backward in time, the uncertainty increases so that at 200 m.yr., the uncertainty in plate positions is ±5° of latitude, and at 300 m.yr., the uncertainty in plate position is ±10° of latitude. Simply stated, the location of any continent on the plate tectonic reconstruction for 200 m.yr. might be 5° (550 km) too far north or too far south. At 300 m.yr., the location of any continent might be 10° (1100 km) too far north or too far south.

It is clear from figure 2 that the uncertainty in plate position increases exponentially backward through time. Three different estimates of uncertainty, however, are shown. The dashed line represents average uncertainty. The dark gray line is an estimate of uncertainty based on the assumption that there were no Late Precambrian supercontinents. In this case, it is clear that no reliable reconstructions can be made for the Late Precambrian because the uncertainties in plate position exceed ±45° of latitude. The light gray dashed line is a more optimistic estimate that supposes that there were two Late Precambrian supercontinents (Pannotia and Rodinia). In that case, the overall uncertainty in plate position is lower because it is easier to know the orientation of one large continent than it is to know the location of several widely dispersed continents (the Pangea principle).

The black line with the open and filled circles is a more detailed estimate of the uncertainties for specific time intervals. For the past 200 m.yr., the solid black curve falls along the dashed curves. For older times, the degree of uncertainty decreases when the continents are gathered together in a supercontinent and increases when the continents are dispersed. The uncertainties in plate position for the time interval covered in this article are quite acceptable, ranging from ±5° (550 km) to a maximum of ±12° (1330 km) in the Triassic when the continents in the eastern hemisphere (Cimmeria and Cathaysia) were more widely dispersed.

Concluding Remarks

Though these simple maps (fig. 3) review plate motions during the past 750 m.yr., they are little more than a sketch of what could be done, and what I believe will be done, during the next decades. As online digital geological databases become increasingly available on the Internet (Geoinformatics), and as geographic information systems technology becomes more useful and widely used, it is likely that we will see a renaissance in the mapping of plate motions and earth history. In the future, these high-resolution digital reconstructions of the earth's changing features will provide a new framework for a greater understanding of earth system history. This spatial/temporal framework is necessary if we are to understand the complex history of climate change, oceanographic change, biogeographic change, and the evolution of life on this amazing planet.

More than 500 yr ago, Christopher Columbus began a voyage into the unknown. As a result, the true extent and geography of the world were discovered. We have just begun a similar voyage. But this voyage of discovery, a discovery of the earth's past, will take us on a journey through time as well as space.

ACKNOWLEDGMENTS

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