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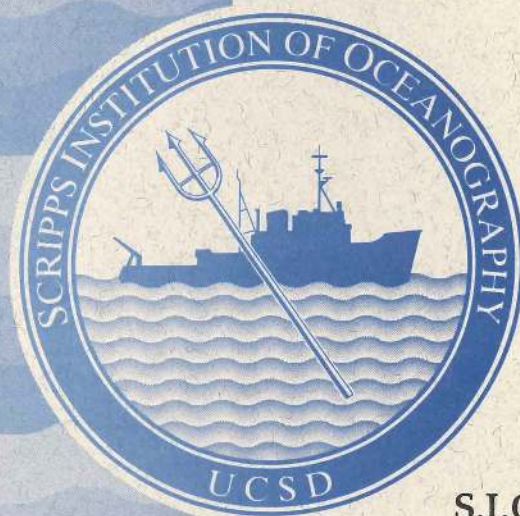
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A Digital Age Map of the Ocean Floor

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ABSTRACT

We have created a digital age grid of the ocean floor with a grid node interval of 6 arc minutes using a self-consistent set of global isochrons and associated plate reconstruction poles. The age at each grid node was determined by linear interpolation between adjacent isochrons in the direction of spreading. Ages for ocean floor between the oldest identified magnetic anomalies and continental crust were interpolated by estimating the ages of passive continental margin segments from geological data and published plate models.

INTRODUCTION

The age of the ocean floor is an important parameter in the study of plate tectonic processes. An accurate digital age grid is essential for many studies, including plate kinematics, studies of plate driving forces, mantle dynamics, ocean floor roughness and paleoceanography. Several analog maps of the age of the ocean floor have been compiled using magnetic anomaly data [e.g. *Sclater et al.*, 1981; *Larson et al.*, 1985]. A digital version of the latter map was produced by *Cazenave et al.* [1988], at a grid interval of half a degree (approx. 55 km). There are several reasons for the construction of a more detailed age grid. First, the isochrons on Larsen et al.'s [1985] age map are not self-consistent. Therefore isochrons on different plates were constructed independently from each other on conjugate plates, and implies that conjugate isochrons do not reconstruct given any rotation pole. Hence they do not represent isochrons *sensu stricto*. Second, recent improvements in identifications of magnetic anomalies and plate kinematic models permit a more detailed description of the spreading process. Finally, world-wide sets of geophysical data (such as bathymetry and gravity) are now available at grid intervals of 5 arc-minutes [*NGDC*, 1988, *Sandwell and Smith*, 1992].

OCEAN FLOOR ISOCHRONS

Royer et al. [1992] constructed a global set of isochrons for the ocean basins corresponding to magnetic anomalies 5, 6, 13, 18, 21, 25, 31, 34, M-0, M-4, M-10, M-16, M-21, M-25 and M-29. The geomagnetic time scale of *Cande and Kent* [1992] was used for anomalies younger than chron 34 (83 Ma), the DNAG scale [*Kent and Gradstein*, 1986] for older times. A self-consistent set of isochrons was constructed by Royer et al. [1992] based on a global plate reconstruction model, magnetic anomaly identifications and fracture zones. This was done by plotting a reconstructed map for each isochron time, keeping one plate fixed. These plots included reconstructed magnetic anomaly and fracture zone picks, as well as selected small circles computed from stage rotation poles. Then continuous isochrons were constructed, connected by transforms. The paleo-ridge segments were drawn by finding the best average lines for superimposed magnetic anomaly picks. The positions of paleo-ridge segments were determined by offsets in magnetic lineations and by mapped fracture zones either from seafloor topography or satellite altimetry data. The fracture zone segments were drawn following small circles about stage rotation poles. This procedure, also described in *Müller et al.* [1990], yielded isochrons in the framework of one fixed plate. A complete set of isochrons for all

conjugate plate pairs was derived by rotation of every isochron to their present day position. The finite rotation poles that this model is based on are compiled in *Royer et al.* [1992].

PRESENT DAY PLATE BOUNDARIES

Construction of a complete age grid requires knowledge of the present day plate boundary geometry. The boundaries shown on Figure 1 have been compiled based on Geosat exact repeat mission and Geodetic Mission data [*Sandwell and Smith, 1992*], bathymetric data, and earthquake epicenters.

BOUNDARIES BETWEEN OCEANIC AND CONTINENTAL CRUST (COB)

There is a significant area of ocean floor that is older than the oldest mapped isochrons. In order to estimate ages for the oldest ocean floor in ocean basins bounded by passive margins, we assigned ages to continental margin segments based on geological data and published plate models. Because many ocean basins formed by rift propagation, the boundaries between continental and oceanic crust (COB's) of various plates have to be separated into a number of segments with different assigned ages. The references for the COB's in the North and central North Atlantic have been summarized by *Müller and Roest* [1992], and for the South Atlantic by *Nürnberg and Müller* [1992]. References for the Indian ocean and other areas can be found in *Royer et al.* [1992]. South of 60°S a dense grid of Geosat Geodetic Mission data [*Sandwell and Smith, 1992*] has been used to better locate boundaries between continental and oceanic crust in remote areas such as the Antarctic continental margin.

INTERPOLATION OF ISOCHRON AGES

In order to create a smooth grid of ocean floor ages that maintains all sharp age discontinuities at fracture zones, we created a set of densely interpolated isochrons. We assume that the spreading direction between two adjacent isochrons is given by a constant pole of motion, derived from plate kinematic models. We also assume that the spreading velocity between two adjacent isochrons is constant, and that consequently the age varies linearly in the direction of spreading. To simplify the calculations, each pair of adjacent isochrons is transformed to a coordinate system where the pole of motion between the two isochrons is the north pole [*Roest et al., 1992*]. Then intermediate isochrons were linearly interpolated along plate flow lines. In a stage pole reference frame, this is equivalent to interpolation along east-west parallels. The complete set of isochrons for each stage was subsequently rotated back into the present day framework. This was done for each isochron pair on each plate pair. Fig. 1 shows the result of isochrons interpolated in 1 m.y. intervals for the South Atlantic.

OCEAN FLOOR AGE GRID

To interpolate the ages onto a regular grid, we assume that the isochrons are continuous, which is implemented by densely interpolating between observation points along each isochron. A minimum curvature routine [*Smith and Wessel, 1990*] is used to

obtain age values on a regular grid at a resolution of 0.1 degrees, equivalent to 6 arc minutes. Areas of the ocean floor with insufficient data coverage were blanked out in the grid. We included data from selected back arc basins into our grid, where data coverage is sufficient. The resolution of our grid for these areas is typically reduced by a factor of 10 with respect to the oceanic grid, i.e. the resolution in back-arc basins does not exceed 1 degree, and provides merely a rough estimate of the age distribution in these basins.

We used the resulting grid to create a color-coded, shaded map of the ages of the world's oceans. This map is available from the SIO Geological Data Center (see Appendix for details). A reduced black and white version of this map is shown on Figure 2. The digital file with age values of the world's oceans will ultimately be accompanied by several additional data sets, containing, for example, error estimates, local spreading directions and rates, and the paleolatitude at which the crust is inferred to have formed. The digital grid is available at a public ftp site at SIO (see Appendix).

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APPENDIX.

The digital age grid is available at an anonymous ftp site at [baltica.ucsd.edu](ftp://baltica.ucsd.edu) (132.239.121.66). Copies of the map can be obtained from:

Within the USA: The *Geological Data Center, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0223, USA*, Ph. (619) 534 2752. Price: US\$ 40. Methods of payment: Purchase order or check.

Outside the USA: The *Geophysical Data Center, Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario K1A 0Y3, Canada*, Ph. (613) 995 5326. Price: CAN\$ 50. Methods of payment: Visa, Mastercard (provide name, on card, number, and expiration date), or international money order. Prices are subject to change.

REFERENCES

- Cande, S.C. and D.V. Kent, 1992, A new geomagnetic polarity time scale for the late Cretaceous and Cenozoic, J. Geophys. Res., 97, 13917-13951.
- Cazenave, A., Domihh, K., Rabinowicz, M. and Ceuleneer, G., 1988, Geoid and depth anomalies over ocean swells and troughs: evidence of an increasing trend of the geoid to depth ratio with age of plate: J. Geophys. Res. 93, 8064-8077.
- Kent, D.V. and Gradstein, F.M., 1986, A Jurassic to recent chronology, in: Vogt P.R. and Tucholke, B.E., Eds., The Geology of North America, Vol. M, The Western North Atlantic Region, Geological Society of America, Boulder, Colorado, 45-50.
- Larson R.L., Pitman, W.C., Golovchenko, X., Cande, S.D., Dewey, J.F., Haxby, W.F. and Labreque, J.L., 1985, Bedrock geology of the world: Freeman, New York.
- NGDC (National Geophysical Data Centre), 1988, ETOPO-5 Bathymetry/Topography Data, Data Announcement 88-MGG-02: National Oceanic and Atmospheric Administration, U.S. Department of Commerce.
- Roest, W.R., Müller, R.D. and Verhoef, J., 1992, Age of the ocean floor: A digital data set for the Labrador Sea and Western North Atlantic, Geoscience Canada, 19, 27-32.
- Royer, J.-Y., R.D. Müller, L.M. Gahagan, L.A. Lawver, C.L. Mayes, D. Nürnberg, and J.G. Sclater, 1991, A global isochron chart, UTIG Technical Report Nr. 117.
- Wessel P. and Smith W.H.F., 1991, EOS Trans. Amer. Geophys. Union, 72 (41).
- Sandwell, D.T., and W.H.F. Smith, Global marine gravity from ERS-1, Geosat and Seasat reveals new tectonic fabric, EOS Trans. Am. Geophys. Union, 73, 133.
- Sclater, J.G., Parsons, B. and Jaupart, C., 1981, Oceans and continents: similarities and differences in the mechanism of heat loss: J. Geophys. Res., 86, 11535-11552.
- Smith, W. H. F., and P. Wessel, Gridding with continuous curvature splines in tension, Geophysics, 55, 293-305, 1990.

REFERENCES FOR MAGNETIC AND FRACTURE ZONE DATA BY REGION:

Scotia Sea

- British Antarctic Survey, 1985, Tectonic Map of the Scotia Arc, Scale 1:3,000,000. BAS (Misc.) 3. Cambridge, British Antarctic Survey.
- LaBrecque, J.L. and Cande, S.C., 1986, Total intensity magnetic anomaly profiles, Northwest Ocean Margin Drilling Program, Regional Data Synthesis Series, Atlas 13, S. Atlantic Ocean and Adjacent Antarctic Continental Margin.

Japan and Korea

- Otsuki, K. and Ehiro, M., 1979, Major strike-slip faults and their bearing on spreading in the Japan Sea, in Uyeda, S., Murphy, R.W., and Kobayashi, K. (eds.), Geodynamics of the Western Pacific, Proceedings of the International Conference on Geodynamics of the Western Pacific-Indonesian Region, March 1978, Tokyo, Advances in Earth and Planetary Sciences, vol. 6, pp. 537-555.

S.E. China, Indochina, Indonesia, Philippines

- Hamilton, Warren, 1978, Tectonic map of the Indonesian region, USGS Survey, Map I-875-D, Reston, Va.
- Hayes, D.E. and Taylor, B., 1978, A geophysical atlas of the East Southeast Asian Seas, GSA Map and Chart Series MC-25, Washington, D.C.
- Mammerickx, J., Fisher, R.L., Emmel, K.J., and Smith, S.M., 1976, Bathymetry of the East and Southeast Asian Seas, GSA Map and Chart Series MC-17, Washington, D.C.

West Pacific Marginal Basins

- Hamilton, Warren, 1978, Tectonic map of the Indonesian region, USGS Survey, Map I-875-D, Reston, Va.
- Hayes, D.E. and Taylor, B., 1978, A geophysical atlas of the East and Southeast Asian Seas, GSA Map and Chart Series MC-25, Washington, D.C.
- Kroenke, L.W., Jouannic, C. and Woodward, P., 1983, Bathymetry of the southwest Pacific, Geophysical Atlas of the southwest Pacific, chart 1, UNIGCP 110, United Nations ESCAP, New York.
- Malahoff, A., Feden, R.H., and Fleming, H.S., 1982, Magnetic anomalies and tectonic fabric of marginal basins north of New Zealand, J. Geophys. Res., 87(B5): 4109-4125.
- Mammerickx, J., Fisher, R.L., Emmel, K.J., and Smith, S.M., 1976, Bathymetry of the East and Southeast Asian Seas, GSA Map and Chart Series MC-17, Washington, D.C.
- Packhorn, G.H. (Ed.), 1982, The evolution of the India-Pacific plate boundaries, Tectonophysics, Special Issue, 87: 1-397.
- Watts, A.B., Weissel, J.K., and Davey, F.J., 1977, in Talwani, M. and Pittman, W.C., eds., Island Arcs, Deep Sea Trenches and Back-arc Basins, pp. 419-427.

- Weissel, J.K., A.B. Watts, and A. Lapouille, 1982, Evidence for Late Paleocene to Late Eocene seafloor in the southern New Hebrides Basin, Tectonophysics, 87: 185-241.
- Weissel, J.K. and Watts, A.B., 1979, Tectonic evolution of the Coral Sea Basin, J. Geophys. Res., 84(B9): 4572-4582.
- Weissel, J.K. and Hayes, D.E., 1977, Evolution of the Tasman Sea reappraised, Earth Planet. Sci. Letters, 36: 77-84.

Africa

- Cochran, J. R., 1981, The Gulf of Aden: Structure and evolution of a young ocean basin and continental margin, J. Geophys. Res., 86: 263-287.
- Guennoc, P. Pautot, G., and Coutell, A., 1988, Surficial structures of the northern Red Sea axial valley from 23°N to 28°N: time and space evolution of neo-oceanic structures, Tectonophysics Special Issue on The Gulf of Suez and Red Sea rifting, 153: 1-23.

South East Asia

- Hamilton, Warren, 1978, Tectonic map of the Indonesian region, USGS Survey, Map I-875-D, Reston, Va.
- Hayes, D.E. and Taylor, B., 1978, A geophysical atlas of the East and Southeast Asian Seas, GSA Map and Chart Series MC-25, Washington, D.C.
- Mammerickx, J., Fisher, R.L., Emmel, K.J., and Smith, S.M., 1976, Bathymetry of the East and Southeast Asian Seas, GSA Map and Chart Series MC-17, Washington, D.C.

Weddell Sea

- LaBrecque, J.L. and Cande, S.C., 1986, Total intensity magnetic anomaly profiles, Northwest Ocean Margin Drilling Program, Regional Data Synthesis Series, Atlas 13, S. Atlantic Ocean and Adjacent Antarctic Continental Margin.

North Atlantic Ocean

- Emery, K.O. and Uchupi., E., 1984, The Geology of the Atlantic Ocean, Springer, New York, 1050 p.
- Klitgord, K.D. and Schouten, H. 1986, Plate kinematics of the central Atlantic, in Vogt, P.R. and Tucholke, B.E., eds., The Western North Atlantic Region, GSA DNAG vol. M, pp. 351-378.
- Nunns, A.G., 1983, in Bott, M., Saxov, S., Talwani, M. and Thiede, J., eds., Structure and Development of the Greenland - Scotland Ridge, pp. 11-30.
- Olivet, J-L., LePichon, X., Monti, S. and Sichler, B., 1974, Charlie-Gibbs Fracture Zone: Jour. Geophys. Res., vol. 79, NO. 14, 2059 - 2072.
- Roest, W.R. and Srivastava, S.P., 1989, Seafloor spreading in the Labrador Sea: a new reconstruction, Geology, 17: 1000-1004.

- Sandwell, D.T., 1984, Along-track deflection of the vertical from Seasat: GEBCO overlays, NOAA Tech. Memo., NOS NGS-40.
- Srivastava, S.P. and Roest, W.R., 1989, Seafloor spreading history II-IV, in East Coast Basin Atlas Series: Labrador Sea, J.S. Bell (co-ordinator). Atlantic Geoscience Centre, Geologic Survey of Canada, Map sheets L17-2 - L17-6.
- Srivastava, S.P., Verhoef, J. and Macnab, R., 1988, Results from a detailed aeromagnetic survey across the Northeast Newfoundland Margin, Part I: Spreading anomalies and relationship between magnetic anomalies and the ocean-continent boundary. J. Mar. Pet. Geol. 5, No. 4, p. 306-323.
- Talwani, M. and Eldholm, O., 1977, Evolution of the Norwegian -Greenland Sea, GSA Bull., 88: 969-999.
- Vogt, P.R., 1986, Magnetic anomalies of the North Atlantic Ocean, in: Bogt, P.R. and Tucholke, B.E., eds., The Geology of North America, vol. M, The Western North Atlantic Region, GSA, Plate 3.

Central North Atlantic Ocean

- Emery, K.O. and Uchupi., E., 1984, The Geology of the Atlantic Ocean, Springer, New York, 1050 p.
- Klitgord, K.D. and Schouten, H. 1986, Plate kinematics of the central Atlantic, in Vogt, P.R. and Tucholke, B.E., eds., The Western North Atlantic Region, GSA DNAG vol. M, pp. 351-378.
- Müller, R. D. and W. R. Roest, Fracture zones in the North Atlantic from combined Geosat and Seasat data, J. Geophys. Res., 97, 3337-3350 1992.
- Müller, R.D., D.T. Sandwell, B.E. Tucholke, J.G. Sclater, and P.R. Shaw, Depth to basement and geoid expression of the Kane Fracture Zone: A comparison, Mar. Geophys. Res., 13, 105-129, 1991.
- Nunns, A.G., 1983, in Bott, M., Saxov, S., Talwani, M. and Thiede, J., eds., Structure and Development of the Greenland - Scotland Ridge, pp. 11-30.
- Sandwell, D.T., 1984, Along-track deflection of the vertical from Seasat: GEBCO overlays, NOAA Tech. Memo., NOS NGS-40.
- Searle, R., 1980, Tectonic pattern of the Azores spreading centre and triple junction, Earth Planet. Sci. Let., 51: 415-434.

Caribbean Area

- Rosencrantz, E., M.I. Ross, and J.G. Sclater, 1988, Age and spreading history of the Cayman trough as determined from depth, heat flow, and magnetic anomalies, J. Geophys. Res., 93, 2141-2157, 1988.

South Atlantic Ocean

- Cande, S., LaBrecque, J.L., and Haxby, W.B., in prep., Plate kinematics of the South Atlantic: Chron 34 to present, submitted to J. Geophys. Res.
- Cande, S. C., J. L. LaBrecque, and W. F. Haxby, Plate kinematics of the South Atlantic: Chron 34 to present, J. Geophys. Res., 93, 13479-13492, 1988.

- Emery, K.O. and Uchupi, E., 1984, The geology of the Atlantic Ocean, Springer Verlag New York Inc.
- LaBrecque, J.L. and Hayes, D.E., 1979, Seafloor spreading history of the Agulhas Basin, Earth and Planet. Sci. Letters, 45: 411-428.
- Martin, A.K., Goodlad, S.W., Hartnady, C.J.H., and du Plessis, A., 1982, Cretaceous paleopositions of the Falkland Plateau relative to southern Africa using Mesozoic seafloor spreading anomalies, Geophys. J. R. astr. Soc., 71: 567-579.
- Nürnberg, D. and Müller, R.D., 1991, The opening of the South Atlantic from Late Jurassic to present day: Tectonophysics, v. 191, p. 27-53.
- Rabinowitz, P.D. and LaBrecque, J., 1979, The Mesozoic South Atlantic Ocean and evolution of its continental margins, J. Geophys. Res., 84(B11): 5973-6002.

West Indian Ocean

- Bergh, H.W. and Norton, I.O., 1976, Prince Edward fracture zone and the evolution of the Mozambique Basin, J. Geophys. Res., 81: 5221-5239.
- Berth, H.W., and Barrett, D.M., 1980, Agulhas Basin magnetic bight, Nature, 287: 591-595.
- Bergh, H.W., 1987, Underlying fracture zone nature of Astrid Ridge off Antarctica's Queen Maud Land, J. Geophys. Res., 92: 475-484.
- Fisher, R.L., Sclater, J.G. and McKenzie, D., 1971, Evolution of the Central Indian Ridge, GSA Bull. 82: 553-562.
- Goodlad, S.W., Martin, A.K., and Hartnady, C., 1982, Mesozoic magnetic anomalies in the southern Natal Valley, Nature, 295: 686-688.
- Karasik, A.M., Mercuryer, S.A., Mitin, L.I., Sochevanova, N.A., Yanovsky, V.N., 1986, Documents of the Academy of Science of the USSR, 286: 933-938.
- LaBrecque, J.L. and Hayes, D.E., 1979, Seafloor spreading history of the Agulhas Basin, Earth and Planet. Sci. Lett., 45: 411-428.
- Liu, C.S., Curray, J., and McDonald, J.M., 1982, New constraints on the tectonic evolution of the Eastern Indian Ocean, Earth and Planet. Sci. Letters, 331-342.
- Masson, D.P., Kidd, R.B., and Roberts, D.G., 1982, Late Cretaceous sediment sample from the Amirante Passage, western Indian Ocean, Geology, 10: 264-266.
- Norton, I.O. and Sclater, J.G., 1979, A model for the evolution of the Indian Ocean and the breakup of Gondwanaland, J. Geophys. Res., 84: 6803-6830.
- Patriat, P., 1987, Reconstitution de l'évolution du système de dorsales de l'Océan Indien par les méthodes de la cinématique des plaques, Territoire des Terres Australes et Antarctique Françaises (ed.), 308 p., PhD Thesis, Université de Paris VI, France.
- Rabinowitz, P.D. and LaBrecque, J.L., 1979, The Mesozoic South Atlantic Ocean and evolution of its continental margins, J. Geophys. Res., 84: 5973-6002.
- Royer, J.-Y., Patriat, P., Bergh, H.W., and Scotese, C. R., 1988, Evolution of the Southwest Indian Ridge from the Late Cretaceous (anomaly 34) to the Middle Eocene (anomaly 20), Tectonophysics, 155: 235-260.

- Royer, J.-Y., and Schlich, R., 1988, The Southeast Indian Ridge between the Rodriguez Triple Junction and the Amsterdam and Saint-Paul Islands: detailed kinematics for the past 20 Ma, J. Geophys. Res., 93(B11): 13,524 - 13,550.
- Royer, J.Y. and Sandwell, D.T., 1989, Evolution of the Eastern Indian Ocean Since the Late Cretaceous: Constraints from Geosat Altimetry, J. Geophys. Res., 94(B10): 13,755-13,782 (see POMP Progress Report #29 1287).
- Royer, J.-Y., and Chang, T., 1991, Evidence for relative motions between the Indian and Australian plates during the last 20 Myr from plate tectonic reconstructions: Implications for the deformation of the Indo-Australian plate: J. Geophys. Res., 96, 11,779-11,802.
- Schlich, R., 1982, The Indian Ocean: Aseismic ridges, spreading centers and basins, in Nairn, A.E.M., and Stehli, F., The Indian Ocean, 6: 51-147.
- Segoufin, J. and Patriat, P., 1981, Reconstructions de l'océan Indien occidental pour les époques des anomalies M21, m2 et 34, paléoposition de Madagascar, Bull. Soc. Geol. France, 23: 603-607.
- Tapscott, C., Patriat, P., Fisher, R.L., Sclater, J.G., Hoskins, H., and Parsons, B., 1980, The Indian Ocean triple junction, J. Geophys. Res., 85: 4723-4739.
- Whitmarsh, R.B., 1974, Some aspects of plate tectonics in the Arabian Sea, in R.B. Whitmarsh, O.E. Weser, D.A. Ross, et al., Init. Rep. D.S.D.P., Washington (U.S. Government Printing Office) 23: 527-535.

East Indian Ocean

- Larson, R.L., 1975, Late Jurassic sea-floor spreading in the eastern Indian Ocean, Geology, 3:69-71.
- Larson, R.L., Mutter, J.C., Diebold, J.B., Carpenter, G.B., and Symonds, D., 1979, Cuvier Basin: A product of ocean crust formation by Early Cretaceous rifting off Western Australia, Earth and Planet. Sci. Letters, 45: 105-114.
- Larson R.L., Carpenter, G.B., and Diebold, J.B., 1978, A geophysical study of the Wharton Basin near the Investigator Fracture Zone, J. Geophys. Res., 83(B2): 773-782.
- Markl, R.G., 1974, Evidence for the breakup of Eastern Gondwanaland by the Early Cretaceous, Nature, 251: 196-199.
- Markl, R.G., 1978, Further evidence for the Early Cretaceous breakup of Gondwanaland off Southwestern Australia, Earth and Planet. Sci. Letters, 39: 211-225.
- McKenzie, D. and Sclater, J.G., 1971, The evolution of the Indian Ocean since the Late Cretaceous, Geophys. J. Roy. Ast. Soc., 25: 437-528.
- Norton, I.O. and Sclater, J.G., 1979, A model for the evolution of the Indian Ocean and the breakup of Gondwanaland, J. Geophys. Res., 84: 6803-6830.
- Sclater, J.G., Luyendyk, B.P., and Meinke, L., 1976, Magnetic lineations in the southern part of the Central Indian Basin, GSA Bull., 87: 371-378.
- Veevers, J.J., 1986, Breakup of Australia and Antarctica estimated as mid-Cretaceous (95±5 Ma) from magnetic and seismic data at the continental margin, Earth Planet. Sci. Lett., 77: 91-99.

- Veevers, J.J., Tayton, J.W., Johnson, B.D., and Hansen, L., 1985, Magnetic expression of the continent-ocean boundary between the western margin of Australia and the Eastern Indian Ocean, J. Geophys., 56: 106-120.
- Vogt, P.R., Cherkis, N.Z., Morgan, G.A., 1983, Project Investigator I: Evolution of the Australia-Antarctic discordance deduced from a detailed aeromagnetic survey, Antarctic Earth Science, 608-613.
- Weissel, J.K. and Hayes, D.E., 1972, Magnetic anomalies in the Southeast Indian Ocean, in Antarctic Oceanology II - The Antarctic - New Zealand Sector, D.E. Hayes(ed.), Am. Geophys. Union., Ant. Res. Ser., 19: 165-196.

Central Pacific Ocean

- Handschumacher, D.W., 1976, Post-Eocene plate tectonics of the Eastern Pacific, in The Geophysics of the Pacific Ocean Basin and its Margins, in The Geophysics of the Pacific Ocean Basin and its Margins, AGU Monograph 19, ed.G.H.Sutton, et al., Washington: AGU, pp. 177-202.
- Herron, E.M., 1972, Sea-floor spreading and the Cenozoic history of the east-central Pacific, GSA Bull., 83: 1671-1692.
- Handschumacher, D.W., Pilger, R.H. Jr., Foreman, J.A., and Campbell, J.F., 1981, Structure and evolution of the Easter plate, GSA Memoir 154, pp. 63-76.
- Klitgord, K.D. and Mammerickx, J., 1982, Northern East Pacific Rise: Magnetic anomaly and bathymetric framework, J. Geophys. Res., 87, 6725-6750.
- Mammerickx, J., Herron, E.M., and Dorman, L., 1980, Evidence for two fossil spreading ridges in the southeast Pacific, GSA Bull., 91: 263-271.
- Pardo-Casas, F. and Molnar, P., 1987, Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time, Tectonics, 6(3): 215-232.

South Pacific Ocean

- Barker, P.F., 1982, The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: ridge crest-trench interactions, J. Geol. Soc. London, 139: 787-801.
- Cande, S.C., Herron, E.M., and Hall, B.R., 1982, The early Cenozoic history of the southeast Pacific, Earth Planet. Sci. Letters, 57: 47-62.
- Christofel, D.A. and Falconer, R.F., 1972, Marine magnetic measurements in the southwest Pacific Ocean and the identification of new tectonic features, Antarctic Oceanology II - The Antarctic - New Zealand Sector.
- Molnar, P., Atwater, T., Mammerickx, J., and Smith, S.M., 1975, Magnetic anomalies, bathymetry, and the tectonic evolution of the South Pacific since the Late Cretaceous, Geophys. J.R. Astr. Soc., 40: 383-420.
- Weissel, J.K., Hayes, D.E., and Herron, E.M., 1977, Plate tectonics synthesis: the displacements between Australia, New Zealand, and Antarctica since the Late Cretaceous, Marine Geology, 25: 231-277.
- Stock, J. and Molnar, P., 1987, Revised history of early Tertiary plate motion in the southwest Pacific, Nature, 325: 495-499.

North Pacific Ocean

- Cande, S.C., Larson, R.L., and LaBrecque, J.L., 1978, Magnetic lineations in the Pacific Jurassic Quiet Zone, Earth Planet. Sci. Letters, 41: 434-440.
- Caress, D.W., Menard, H.W., and Hey, R.N., 1988, Eocene reorganization of the Pacific-Farallon Spreading Center north of the Mendocino Fracture Zone, J. Geophys. Res., 93: 2813-2838.
- Currie, R.G., Seeman, D.A., and Riddihough, R.P., 1982, Total field magnetic anomaly offshore British Columbia, Geological Survey of Canada Open-File Report 828, scale 1:1,000,000.
- Elvers, D., Potter, K., Seidel, D., and Morley, J., 1972, IDOE 1971 survey: Washington, D.C., National Oceanographic and Atmospheric Administration, National Ocean Survey Seemap Profiles Plate BGM-1-71.
- Elvers, D.J., Mathewson, C.C., Kohler, R.E., and Moses, R.L., 1967, Systematic ocean surveys by the USC and GSS Pioneer 1961-1963: Coast and Geodetic Survey Operational Data Report C and GSDR-1, 19 P.
- Hayes, D.E. and Taylor, B., 1978, A geophysical atlas of the East and Southeast Asian Seas, GSA Map and Chart Series MC-25, Washington, D.C.
- Hamilton, Warren, 1978, Tectonic map of the Indonesian region, USGS Survey, Map I-875-D, Reston, Va.
- Hilde, T.W.C., Isezki, Nobuhiro, and Wageman, J.M., 1976, in The Geophysics of the Pacific Ocean Basin and its Margins, p. 205-226 (Geophys. Mono. 19).
- Klitgord, K.D. and Mammerickx, J., 1982, Northern East Pacific Rise: Magnetic anomaly and bathymetric framework, J. Geophys. Res., 87, 6725-6750.
- Lonsdale, P., 1991, Structural patterns of the Pacific floor offshore of Peninsula California, in The Gulf and Peninsular Province of the Californias, J. Paul Dauphin and Bernd R.T. Simoneit eds., Am. Assoc. Pet. Geol. Memoir, 47, 87-125.
- Mammerickx, J. and Sharman, G.F., 1988, Tectonic evolution of the North Pacific during the Cretaceous Quiet Period, J. Geophys. Res., 93: 3009-3024.
- Mammerickx, J. Naar, D.F., and Tyuce, R.L., 1988, The Mathematician Paleo-plate, J. Geophys. Res., 93: 3025-3040.
- Mammerickx, J., Fisher, R.L., Emmel, K.J., and Smith, S.M., 1976, Bathymetry of the East and Southeast Asian Seas, GSA Map and Chart Series MC-17, Washington, D.C.
- Nakanishi, M., Tamaki, K., and Kobayashi, K., 1989, Mesozoic magnetic anomaly lineations and seafloor spreading history of the Northwestern Pacific, J. Geophys. Res., 94(B11): 15,437-15,462.
- Renkin, M., Master's thesis, The Univ. of TX at Austin, 1986.
- Raff, A.D. and Mason, R.G., 1961, Magnetic survey off the west coast of North America, 40°N Latitude to 52°N Latitude, GSA Bull., 72: 1267-1270.
- Sharman, G.F. and Risch, D.L., 1988, Northwest Pacific tectonic evolution in the mid-Mesozoic, Tectonophysics, 155, 331-344.

- Tamaki, K., Toshima, M. and Larson, R.L., 1979, Remnant Early Cretaceous spreading center in the central Pacific Basin, J. Geophys. Res., 84: 4501-4510.
- Theberge, A.E., Jr., 1971, Magnetic survey off southern California and Baja California: Rockwel, Maryland, National Oceanographic and Atmospheric Administration, National Ocean Survey, scale 1:1,000,000.

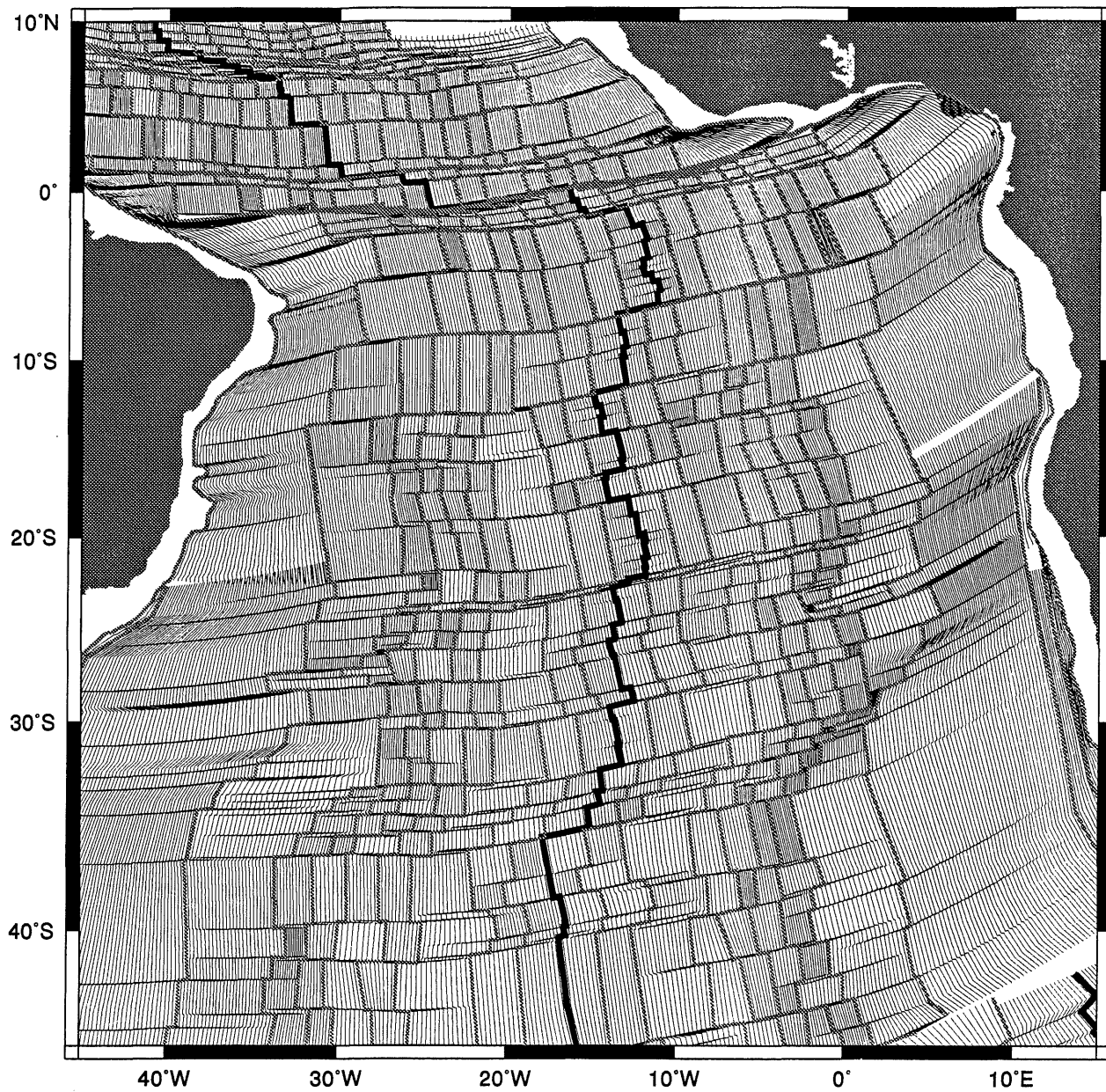


Fig. 1. Seafloor spreading isochrons in the South Atlantic, interpolated in 1 m.y. intervals. Broad grey lines delineate the isochrons bounding the individual interpolated stages. The isochrons correspond to magnetic anomalies 5, 6, 13, 18, 21, 25, 31, 34, M-0, M-4, M-10, M-16, M-21, M-25.

Fig. 2.

A Digital Age Map of the Ocean Floor

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