

[6]

EARLY CENOZOIC GLOBAL PLATE REORGANIZATION

PETER A. RONA and EVAN S. RICHARDSON *

*National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratories,
Miami, FL 33149 (U.S.A.)*

Received November 9, 1977

Revised version received February 28, 1978

Synthesis of regional plate movements reveals a major reorganization of global plate motion from Mesozoic to Cenozoic patterns that occurred primarily during the Eocene epoch (53.5 to 37.5 m.y. B.P.). The reorganization involved reorientation of relative plate motions with large N-S components into large E-W components, continuation of pre-existing E-W sea floor spreading, initiation of new E-W spreading, deceleration of spreading rates, and obduction of ophiolites. The reorganization is attributed to increase in resistance imposed on the global plate system by increase in length of E-W-trending collisional plate boundaries from 2500 to 28,500 km during the interval 55 to 40 m.y. B.P., forcing the system to reorient along lines of less resistance. The pattern of global plate motion resulting from the reorganization is constrained by the resistance imposed by 19,000 km of collisional plate boundaries.

1. Introduction

The extensive literature treating regional plate motions of Mesozoic and Cenozoic age provides a basis for determining global patterns of plate motions and evaluating the degree of interaction between plates. The Early Mesozoic beginning of the breakup and dispersion of Pangaea is a recognized time of global plate reorganization [1]. Synthesis of regional information on sea floor spreading (Table 1), orogenic activity (Table 1), and obduction of ophiolites (Table 2), evidences a global plate reorganization from Mesozoic to Cenozoic patterns of plate motion during the interval between 55 and 40 m.y. B.P. The interval includes portions of the Paleocene (65 to 53.5 m.y. B.P.) and Eocene (53.5 to 37.5 m.y. B.P.), employing revised time scales for the Cretaceous [2], the Cenozoic [3], and for magnetic polarity reversals [4].

* Also University of Miami, Rosenstiel School of Marine and Atmospheric Sciences, Miami, Florida 33149, U.S.A.
Present address: Deep Sea Exploration, Phillips Petroleum Company, Bartlesville, Oklahoma 74004, U.S.A.

2. Regional plate reorganization

Consideration of regional plate motions follows a global circuit of plate boundaries from the Indian Ocean, to the Pacific, Arctic, Atlantic, Caribbean, Mediterranean, and Red Sea. Pertinent information and references are summarized in Tables 1 and 2, so the text will simply outline major events with reference to the tables and to Figs. 1 and 2.

Plate reorganization in the Indian Ocean region involved reorientation of the oceanic ridge system from a predominantly E-W trend that had prevailed since about 100 m.y. B.P., to a NW-SE trend beginning between 53 and 50 m.y. B.P. (Table 1, Fig. 1). The ridge orientation was nearly synchronous with the inferred time of initial collision and decrease in rate of relative motion between India and Eurasia (55 to 40 m.y. B.P.), termination of ophiolite obduction at the Indus suture zone (49 m.y. B.P.; Table 2), and marked decrease in rate of sea floor spreading (approximately 50%; 53 to 40 m.y. B.P.; Table 1). A change in pattern of plate motion occurred south of Australia. Sea floor spreading about a nearly N-S-trending ridge system ended in the Tasman Sea (59 to 56 m.y. B.P.),

TABLE 1

Regional plate motions (see Figs. 1, 2)

Region	Event	Time (evidence)	Reference
Indian Ocean	Beginning of continental collision between India and Eurasia	55 to 40 m.y. B.P. (structural and stratigraphic relations)	[5-9]
Indian Ocean	Decrease in sea floor spreading rates between India and Antarctica-Australia by a factor of approximately 2 from >8 to <4 cm/yr (half rate)	53 to 40 m.y. B.P. (magnetic anomalies 21 and 22)	[10-12]
Indian Ocean	Subduction of nearly E-W-trending oceanic ridge between Australia and Eurasia at convergent plate boundary along the southern margin of Eurasia	53 to 32 m.y. B.P. (magnetic anomalies 11 and 22)	[10]
Indian Ocean	Reorientation of oceanic ridge system from nearly E-W to NW-SE with concomitant change in sea floor spreading direction from nearly N-S to NE-SW.	53 to 50 m.y. B.P. (magnetic anomalies 21 and 22)	[10,13]
Indian Ocean	Ending of sea floor spreading with large E-W component in Tasman Sea	59 to 56 m.y. B.P. (after magnetic anomaly 25)	[14]
Indian Ocean	Beginning of sea floor spreading with large N-S component between Australia-Broken Ridge and Antarctica-Kerguelen Plateau	53 to 50 m.y. B.P. (magnetic anomalies 21 and 22)	[15]
Indian Ocean	Decrease in rate of relative motion between India and Eurasia plates by a factor of approximately 2 from about 10 to 5 cm/yr	50 to 38 m.y. B.P. (magnetic anomalies)	[11,9]
South Pacific	Decrease in rate of sea floor spreading by a factor of approximately 2 from about 5 to 2.3 cm/yr	56 m.y. B.P. (magnetic anomaly 24)	[18,19]
South Pacific	Collision between Australian shield and New Guinea island arc	49 to 43 m.y. B.P. (Middle Eocene; structural and stratigraphic relations)	[16]
South Pacific	Beginning of sea floor spreading west of Scotia Sea	54 to 30 m.y. B.P. (magnetic anomalies)	[20]
South Pacific	Rifting of South America from Antarctic peninsula	54 to 30 m.y. B.P. (magnetic anomalies)	[20]
North Pacific	Laramide orogeny predominantly E-W compressive deformation and plutonism in western North America and northwestern South America	80 to 40 m.y. B.P.	[21]
North Pacific	Change in direction of sea floor spreading from ENE-WSW to E-W evidenced by Zed pattern of magnetic anomalies and trends of fracture zones	55 to 50 m.y. B.P. (magnetic anomalies 21 to 23)	[22,13]
North Pacific	Beginning of subduction along Philippine, Bonin, Marianas, Yap, Palau, and Tonga trench-arc systems	Shortly after 45 m.y. B.P. (maximum ages and trends of associated island arcs)	[23-25]
North Pacific	Change in direction of plate motion from NNW to WNW with respect to Hawaiian hot spot evidenced by Emperor Seamount-Hawaiian Ridge bend	43 to 41 m.y. B.P. (radiometric dating)	[26]
Arctic	Beginning of sea floor spreading in an E-W direction about the Gakkel Ridge resulting in opening of the Eurasian Basin	63 m.y. B.P. (magnetic anomalies)	[27,28]

TABLE 1 (continued)

Region	Event	Time (evidence)	Reference
North Atlantic	Duration of sea floor spreading in the Norwegian Basin	56 to 42 m.y. B.P. (magnetic anomalies)	[29]
North Atlantic	Beginning of spreading at Iceland–Jan Mayen Ridge	42 m.y. B.P. (magnetic anomalies)	[29]
North Atlantic	Duration of second episode of sea floor spreading in the Labrador Sea	56 to 44 m.y. B.P. (magnetic anomalies 19 to 24)	[30,31]
North Atlantic	Beginning of spreading on Reykjanes Ridge	56 m.y. B.P. (magnetic anomaly 24)	[32,33]
North Atlantic	Change in spreading direction on Reykjanes Ridge from indeterminate to E-W	40 m.y. B.P. (magnetic anomalies)	[32,33]
North Atlantic	Decrease in rate of sea floor spreading north of the Azores-Gibraltar lineament by a factor of approximately 2 from about 2.5 to 1.0 cm/yr	59 to 50 m.y. B.P. (magnetic anomalies 21 to 25)	[27]
North Atlantic	Decrease in rate of sea floor spreading south of the Azores-Gibraltar lineament by a factor of approximately 1.5 from about 1.7 to 1.2 cm/yr	59 to 50 m.y. B.P. (magnetic anomalies 21 to 25)	[27,34]
North Atlantic	Change in relative direction of spreading from nearly E-W to WNW-ESE evidenced by bend in Kane fracture zone	59 to 50 m.y. B.P. (magnetic anomalies 21 to 25)	[35]
South Atlantic	No apparent changes in sea floor spreading rate and direction based on limited data	72 to 0 m.y. B.P. (axial magnetic anomaly to anomaly 31)	[36–38]
Caribbean	Separation of Caribbean plate from Pacific plate as a consequence of southward extension of the Middle Americas Trench	54 to 38 m.y. B.P. (Eocene age of earliest volcanics in Central America)	[39]
Caribbean	Jump of subduction zone from Aves Ridge to Lesser Antilles island arc	54 m.y. B.P. (60 m.y. B.P. radiogenic date of granodiorite from Aves Ridge; 54 m.y. B.P. initiation of volcanism in Lesser Antilles)	[40,39]
Caribbean	Collision of Bahama Banks with Greater Antilles (Cuba)	Post-70 to 43 m.y. B.P. (Late Cretaceous to Middle Eocene based on structural relations)	[41,42]
Caribbean	End of N-S subduction at Puerto Rico	49 to 43 m.y. B.P. (Middle Eocene radiogenic age of youngest volcanic rocks present)	[42]
Caribbean	Beginning of present Puerto Rico Trench	Post-43 m.y. B.P. (post-Middle Eocene based on structural and stratigraphic relations)	[43–45]
Caribbean	End of N-S subduction at Cuba	49 to 43 m.y. B.P. (Middle to Late Eocene based on structural relations)	[41,44]
Caribbean	End of N-S subduction at Hispaniola	Prior to 43 m.y. B.P. (pre-Late Eocene based on stratigraphic relations)	[46]
Caribbean	General change of plate motion from N-S compression to E-W strike slip	54 to 38 m.y. B.P. (Eocene based on structural relations at northern and southern boundaries of Caribbean plate)	[39]
Caribbean	Beginning of sea floor spreading in present Cayman Trough	49 to 43 m.y. B.P. (Middle Eocene based on estimated spreading and sedimentation rates)	[47,48]
Mediterranean	Right lateral E-W strike slip motion along Tethys	80 to 53 m.y. B.P. (deduced from relative plate motions in the North Atlantic)	[49]
Mediterranean	Change to N-S collision, compression and subduction along Tethys	53 m.y. B.P. (deduced from relative plate motions in the North Atlantic)	[49]

TABLE 1 (continued)

Region	Event	Time (evidence)	Reference
Mediterranean	Collision of Iberian peninsula with Eurasia	54 to 38 m.y. B.P. (Eocene based on structural relations)	[50]
Mediterranean	Beginning of deformation of Betic mountains in southern Spain	49 to 43 m.y. B.P. (Middle Eocene based on structural relations)	[49]
Mediterranean	Possible reversal of subduction polarity in Swiss Alps	49 to 43 m.y. B.P. (Middle Eocene based on structural relations)	[51]
Mediterranean	Meso-Alpine orogeny involving main movements of Penninic and Austroalpine nappes in Swiss Alps	43 to 38 m.y. B.P. (Late Eocene to Early Oligocene based on structural relations)	[52]
Mediterranean	Subduction in Tellian Atlas and Sicilides	54 to 38 m.y. B.P. (Eocene based on active flysch sedimentation)	[49]
Mediterranean	End of subduction in eastern Alps as a consequence of continental collision	45 to 42 m.y. B.P. (structural and stratigraphic relations)	[53]
Mediterranean	Orogeny in High Atlas and Saharan Atlas	43 to 30 m.y. B.P. (post-Middle Eocene and pre-Middle Oligocene based on structural and stratigraphic relations)	[54,55]
Red Sea	Beginning of sea floor spreading with large E-W component	38 m.y. B.P. (magnetic anomalies)	[56]

TABLE 2

Early Cenozoic ophiolites (see Figs. 1, 2)

Region	Location	Age of obduction (evidence)	Reference
Indian Ocean	Indus suture zone of the Himalayas	100 to 49 m.y. B.P. (Late Cretaceous through Early Eocene based on Eocene age of youngest ophiolites and of granites that intrude ophiolites)	[6]
Indian Ocean	Andaman Islands	53 to 43 m.y. B.P. (Early and Middle Eocene based on overlying Miocene shale and other stratigraphic evidence)	[16]
South Pacific	East Papua and West Irian, New Guinea	52 m.y. B.P. (Early Eocene based on radiometric dating of metamorphic and intrusive rocks in the ophiolites)	[57]
South Pacific	New Caledonia	43 to 37 m.y. B.P. (Late Eocene based on Lower and Middle Eocene sediments underlying ophiolite and ophiolite debris in Upper Eocene flysch)	[58,59]
North Pacific	Philippine Islands	54 to 37 m.y. B.P. (Eocene based on structural relations)	[60]
North Pacific	Knight Island, southern Alaska	65 to 52 m.y. B.P. (Paleocene through Early Eocene age of intrusion of ophiolitic type rocks and trench-type flysch sediments)	[61]
North Pacific	Coastal Cordillera of Venezuela and Western Cordillera of Colombia	54 to 30 m.y. B.P. (Eocene and Early Oligocene based on structural relations)	[62]
Arctic	No Eocene ophiolites known		
North Atlantic	No Eocene ophiolites known		
South Atlantic	No Eocene ophiolites known		
Mediterranean	Eastern Alps	100 to 45 m.y. B.P. (Late Cretaceous to Late Eocene based on structural relations and radiogenic dates)	[53,63]
Mediterranean	Corsica	54 to 37 m.y. B.P. (Eocene)	[49]

and spreading about a nearly E-W-trending ridge system began between Australia–Broken Ridge and Antarctica–Kerguelen Plateau (53 to 50 m.y.; Table 1; Fig. 1).

In the South Pacific region the largest known change in rate of sea floor spreading during the past 72 m.y. is inferred to have occurred about 56 m.y. B.P. (Table 1); no major changes of direction are known to have accompanied the spreading rate change at that time. Ophiolites were obducted in New Guinea (52 m.y. B.P.; Table 2; Fig. 2) and New Caledonia (43 to 37 m.y. B.P.), possibly related to collision of those islands with the Australian shield (49 to 43 m.y. B.P.; Table 1). Events in the southeastern Pacific (Table 1) require further documentation.

Structures inferred to have been transform faults during the late Mesozoic along the western margin of the South Pacific and North Pacific became subduction zones shortly after 45 m.y. B.P. (Table 1; Fig. 2). This conversion from transform motion to subduction may be related to the changes in direction of sea floor spreading from large N-S to large E-W components in the Indian Ocean as already noted (53 to 50 m.y. B.P.), and in the North Pacific evidenced by trends of magnetic anomalies and fracture zones (55 to 50 m.y. B.P.; Table 1), and the Emperor Seamount–Hawaiian Ridge bend (43 to 41 m.y. B.P.; Table 1; Fig. 2). The large E-W component of relative motion was manifested at the eastern margin of the North Pacific by continued E-W compressive deformation of the Laramide orogeny (80 to 40 m.y. B.P.; Table 1), and in the South Pacific by continued subduction along the western margin of South America (Fig. 2).

In the Arctic region E-W sea floor spreading about the Gakkel Ridge, a northward continuation of the Mid-Atlantic Ridge, began about 63 m.y. B.P. (Table 1; Fig. 1). Several prominent changes in sea floor spreading occurred in the northern North Atlantic during the interval between 56 and 42 m.y. B.P. involving shifts in spreading about essentially N-S ridges (Table 1; Fig. 1). In the North Atlantic marked decreases in rate of sea floor spreading (approximately 50%) about the Mid-Atlantic Ridge occurred both north and south of the Azores–Gibraltar lineament within the interval 59 to 50 m.y. B.P. (Table 1; Fig. 1). A change in relative direction of spreading from nearly E-W to WNW-ESE documented at the Kane fracture zone occurred synchronously with the

change in spreading rate (Table 1; Fig. 1). Limited data from the South Atlantic region do not reveal any apparent major changes in spreading rate or direction in the Early Cenozoic.

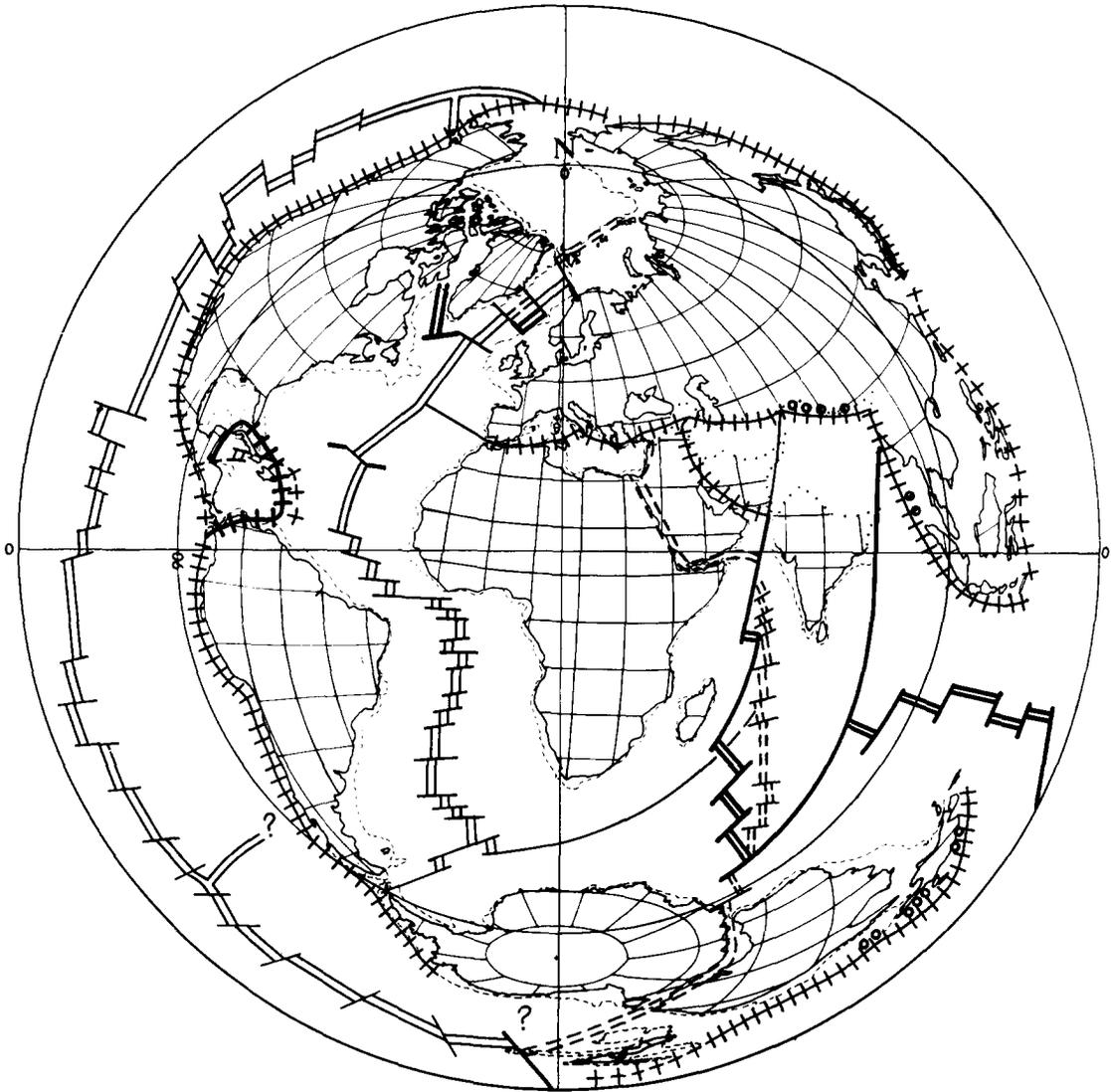
The Caribbean region underwent plate reorganization during the Eocene. A pattern of N-S compression and subduction that had prevailed since about 110 m.y. B.P. at the northern and southern boundaries of the Caribbean plate changed to predominant E-W strike slip motion from 54 to 38 m.y. B.P. (Table 1; Fig. 2). The termination of N-S subduction at the northern margin of the Greater Antilles between 49 and 43 m.y. B.P., and the initiation of the present Puerto Rico (43 m.y. B.P.) and Cayman trenches (49 to 43 m.y. B.P.) manifest this change. The change may not have been synchronous or complete along the southern boundary of the Caribbean as evidenced, for example, by the obduction of ophiolites at the northern margin of South America as recently as 30 m.y. B.P. (Table 2; Fig. 1).

A change in pattern of plate motion in the Mediterranean region was nearly antithetic to that described in the Caribbean region. Right lateral E-W strike slip motion, inferred to have prevailed along the Tethys between 80 and 53 m.y. B.P., changed to N-S compression and subduction at about 53 m.y. B.P. with associated orogenic episodes and ophiolite obduction at the bounding plate margins (Table 1; Fig. 1). In the Red Sea, the final segment in the global circuit of plate boundaries, sea floor spreading with a large E-W component, began about 38 m.y. B.P. (Table 1; Fig. 1).

3. Global plate reorganization

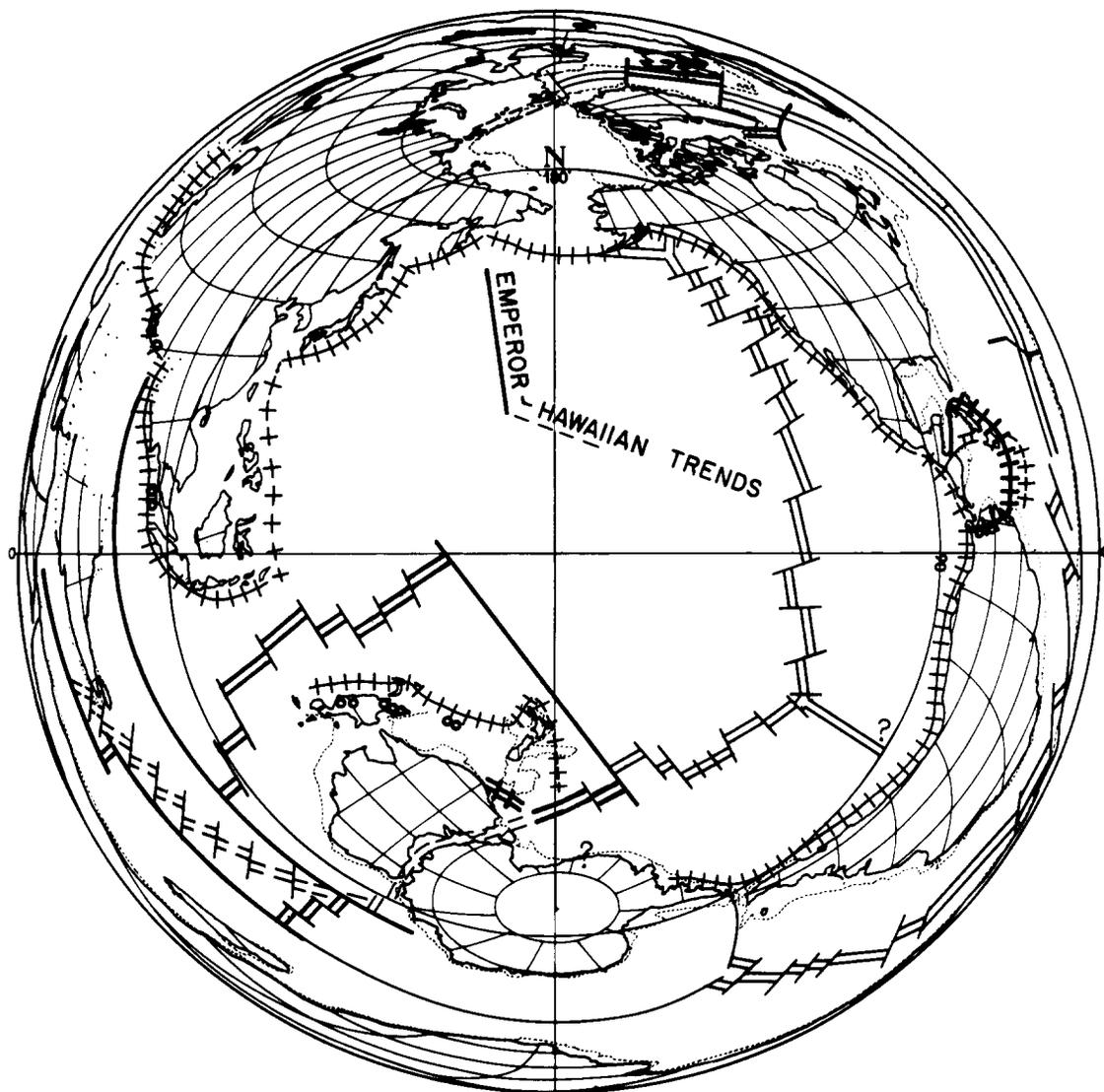
Consideration of the regional changes in plate motion (Table 1; Figs. 1, 2) reveals patterns of Early Cenozoic plate reorganization which occurred primarily during the Eocene (53.5 to 37.5 m.y. B.P.), as follows:

(1) Major reorientation of those relative plate motions with large N-S components to large E-W components. This pattern is exhibited by changes in the direction of spreading in the Indian Ocean (53 to 50 m.y. B.P.) and the North Pacific Ocean (55 to 50 m.y. B.P.), as well as by change in the direction of motion of the North Pacific sea floor with respect



- PRE-REORGANIZATION PLATE BOUNDARY
- - - POST-REORGANIZATION PLATE BOUNDARY
- PLATE BOUNDARY UNAFFECTED BY REORGANIZATION
- ==== DIVERGENT PLATE BOUNDARY
- ++++ CONVERGENT PLATE BOUNDARY
- TRANSFORM PLATE BOUNDARY
- EOCENE OPHIOLITES

Fig. 1. Plate boundaries before and after Early Cenozoic plate reorganization plotted on Lambert equal area projection showing Eocene (50 ± 5 m.y. B.P.) distribution of continents [65]. Front view.



- PRE-REORGANIZATION PLATE BOUNDARY
- - - POST-REORGANIZATION PLATE BOUNDARY
- PLATE BOUNDARY UNAFFECTED BY REORGANIZATION
- ==== DIVERGENT PLATE BOUNDARY
- + + + + CONVERGENT PLATE BOUNDARY
- — — — TRANSFORM PLATE BOUNDARY
- EOCENE OPHIOLITES

Fig. 2. Plate boundaries before and after Early Cenozoic plate reorganization plotted on Lambert equal area projection showing Eocene (50 ± 5 m.y. B.P.) distribution of continents [65]. Back view.

to the Hawaiian hot spot (43 to 41 m.y. B.P.).

(2) Continuation with only minor reorientation of these plate motions with large E-W components and initiation of new E-W relative plate motions. This pattern is exhibited by continued E-W sea floor spreading about the Mid-Atlantic Ridge in the North Atlantic and South Atlantic, and by the initiation of predominantly E-W spreading about centers in the Arctic Ocean (63 m.y. B.P.), the northern North Atlantic Ocean (56 to 42 m.y. B.P.), and the Red Sea (38 m.y. B.P.).

(3) Decrease in rate of sea floor spreading affecting both regions of major and minor reorientation of sea floor spreading (patterns 1 and 2). Such decreases in spreading rate occurred in the Indian Ocean (53 to 40 m.y. B.P.), the South Pacific (56 m.y. B.P.), and the North Atlantic (59 to 50 m.y. B.P.), concurrently with reorientation of spreading direction.

(4) Change in nature of motion at certain plate boundaries between convergence with compression and strike slip. Such change occurred antithetically in two different regions within similar latitudes. In the Caribbean region N-S compression and subduction at E-W-trending convergent plate boundaries changed to predominant E-W strike slip motion (54 to 38 m.y. B.P.). In the Mediterranean region E-W-trending strike slip motion changed to N-S compression at a convergent plate boundary (53 m.y. B.P.).

(5) Conversion of certain transform plate boundaries to convergent plate boundaries as a consequence of major reorientation of plate motions. During the change in direction of sea floor spreading from large N-S to large E-W components in the Indian Ocean and North Pacific regions (55 to 41 m.y. B.P.), inferred pre-existing N-S-trending transform faults along the western margin of the Pacific became subduction zones.

(6) Sequential extinction of one spreading center and initiation of another spreading center with major reorientation of spreading. Such a change occurred within the same region within similar latitudes. The end of E-W spreading in the Tasman Sea (59 to 56 m.y. B.P.) was followed by the beginning of N-S spreading south of Australia (53 to 50 m.y. B.P.).

(7) Obduction of ophiolites at certain convergent plate boundaries involved in reorganization of plate motion in the Indian Ocean (100 to 43 m.y. B.P.), the South Pacific (52 to 37 m.y. B.P.), the North

Pacific (65 to 30 m.y. B.P.), and the Mediterranean (100 to 37 m.y. B.P.) regions (Table 3). Obduction of ophiolites may be a prime indicator of plate reorganization.

4. Global plate interaction

The nature of the plate interactions which produced the observed patterns of Early Cenozoic global plate reorganization may be deduced from assessment of global plate boundaries. The lengths of convergent and divergent plate boundaries were measured and totaled before and after the plate reorganization (Table 3). Regarding convergent plate boundaries, the process of subduction of oceanic crust which offers relatively low resistance to plate convergence, is distinguished from the process of collision involving continental or transitional (island arc) crust which offers relatively high resistance to plate convergence as a consequence of crustal buoyancy.

Immediately preceding the Early Cenozoic plate reorganization the total lengths of convergent and divergent plate boundaries were nearly equal at 52,000 and 50,000 km, respectively (Table 3). Of the 52,000 km of convergent plate boundaries, only about 2500 km in the Zagros area is known to have been a collisional boundary; subduction is inferred to have prevailed at the balance of the convergent plate boundaries (Figs. 1, 2). In the transition interval during the plate reorganization the length of collisional plate boundaries increased to 28,500 km (Table 3) due to the beginning of the collision of India and Eurasia along an E-W-trending boundary (5000 km; 55 to 40 m.y. B.P.), collision of the Australian shield with the New Guinea island arc along an E-W-trending boundary (8000 km; 49 to 43 m.y. B.P.), collision of the Bahama Banks with the Greater Antilles along an E-W-trending boundary region (1500 km; post-70 to 43 m.y. B.P.), and the change from E-W strike slip to N-S collision and compression along an E-W-trending boundary in the Mediterranean region (11,500 km; 53 m.y. B.P.). Shortly following plate reorganization the collisions in the Australian shield—New Guinea island arc (8000 km) and the Bahamas Banks—Greater Antilles (1500 km) stopped, leaving a balance of 19,000 km of collisions in effect (Table 3). The total length of convergent plate bound-

TABLE 3

Early Cenozoic plate organization (see Figs. 1, 2)

All convergent plate boundaries (subduction and collision)

	Length * (km)		
	before	after	net change
South America and North America	17,000	18,000	+1,000
Aleutian-Kurile-Japan	8,000	8,000	0
Philippine-Ryuku-Marianas-Yap	0	9,000	+9,000
Zagros-Indus-Indonesia	14,000	14,000	0
New Guinea-Tonga	8,000	11,500	+3,500
Caribbean	5,000	2,500	-2,500
Mediterranean	0	11,500	+11,500
Worldwide total	52,000	74,500	22,500

Convergent plate boundaries: collision

	Length * (km)		
	before	transition	after
Zagros-Indus-Indonesia	2,500	7,500	7,500
New Guinea-Tonga	0	8,000	0
Caribbean	0	1,500	0
Mediterranean	0	11,500	11,500
Worldwide total	2,500	28,500	19,000

All divergent plate boundaries

	Length * (km)		
	before	after	net change
East Pacific	16,000	16,000	0
Australia-Antarctic-Indian	3,000	12,000	+9,000
Indonesian	10,000	0	-10,000
Red Sea	0	2,000	+2,000
Atlantic-Arctic	19,000	20,000	+1,000
Tasman	2,000	0	-2,000
Worldwide total	50,000	50,000	0

* Measured with estimated 5% accuracy on 40 cm diameter globe.

aries including both subduction and collision had increased to 74,500 km, an addition of 22,500 km over the pre-organizational total, while that of divergent plate boundaries remained at 50,000 km, no change from the pre-reorganizational total.

5. Conclusions

A statement by McKenzie and Sclater [64] with reference to the Indian Ocean region helps to elucidate the global observations presented: "Since the momentum of plates can always be neglected, any change in their motion must involve a change in either the driving forces or the resistive forces." The evidence presented clearly supports the interpretation that the plate reorganization from Mesozoic to Cenozoic patterns of plate motion was primarily a response to the global distribution of resistive forces.

The increase in E-W-trending collisional plate boundaries from about 2500 to 28,500 (5–38% of total length of convergent plate boundaries) during the interval between 55 and 40 m.y. B.P. (Tables 1, 3) produced a corresponding increase in resistance that apparently forced the global plate system to reorganize along lines of less resistance. The reorganization involved reorientation of relative plate motions with large N-S components into large E-W components, continuation of pre-existing E-W sea floor spreading, initiation of new E-W spreading, deceleration of spreading rates, complex antithetic and sequential events limited to certain regions, and obduction of ophiolites. The persistence of about 19,000 km of collisional plate boundaries subsequent to 40 m.y. B.P. has acted to constrain the global pattern of plate motion established by the Early Cenozoic plate reorganization. The occurrence of global plate reorganizations in Early Mesozoic and Early Cenozoic suggests a plate tectonic basis for the division of the Phanerozoic time scale into eras.

Acknowledgements

We thank Steven Schamel for guidance in the structural history of the Mediterranean region. We thank C.G.A. Harrison and Walter C. Pitman III for helpful reviews. This research was supported by NOAA. Contribution from NOAA and the University of Miami, Rosenstiel School of Marine and Atmospheric Sciences.

References

- [1] R.S. Dietz and J.C. Holden, Reconstruction of Pangaea: breakup and dispersion of continents, Permian to

- present, *J. Geophys. Res.* 75 (1970) 4939.
- [2] J.E. Van Hinte, A Cretaceous time scale, *Am. Assoc. Pet. Geol. Bull.* 60 (1976) 498.
- [3] W.A. Berggren, Cenozoic chronostratigraphy, planktonic foraminiferal zonation and the radiometric time-scale, *Nature* 224 (1969) 1072.
- [4] J.L. La Brecque, D.V. Kent and S.C. Cande, Revised magnetic polarity time scale for Late Cretaceous and Cenozoic times, *Geology* 5 (1977) 330.
- [5] A. Gansser, *Geology of the Himalayas* (Interscience, London, 1964) 289.
- [6] A. Gansser, The Indian Ocean and the Himalayas—geological interpretation, *Eclogae Geol. Helv.* (59) 831.
- [7] A. Sahni and V. Kumar, Paleogene palaeobiogeography of the Indian subcontinent, *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 15 (1974) 209.
- [8] P. Le Fort, Himalayas: the collided range. Present knowledge of continental arc, *Am. J. Sci.* 275-A (1975) 1.
- [9] P. Molnar and P. Tapponnier, The collision between India and Eurasia, *Sci. Am.* 236 (1977) 30.
- [10] J.G. Sclater and R.L. Fisher, Evolution of the East Central Indian Ocean with emphasis on the tectonic setting of the Ninetyeast Ridge, *Geol. Soc. Am. Bull.* 85 (1974) 683.
- [11] B.D. Johnson, C. McA. Powell and J.J. Veevers, Spreading history of the eastern Indian Ocean and Greater India's northward flight from Antarctica and Australia, *Geol. Soc. Am. Bull.* 87 (1976) 1560.
- [12] J.W. Pierce, The origin of the Ninetyeast Ridge and the northward motion of India, based on DSDP paleolatitudes, Doctoral Dissertation, Woods Hole Oceanographic Institution (1977) 283.
- [13] W.C. Pitman III, R.L. Larson and E.M. Herron, The Age of the Ocean Basins (*Geological Society of America*, 1974) 2 maps.
- [14] D.E. Hayes and J. Ringis, The early opening of the central Tasman Sea, *EOS, Trans. Am. Geophys. Union* 53 (1972) 413 (abstract).
- [15] J.K. Weissel and D.E. Hayes, Magnetic anomalies in the southeast Indian Ocean; in: *Antarctic Oceanology II: The Australian–New Zealand sector*, D.E. Hayes, ed., *Am. Geophys. Union, Antarctic Res. Ser.* 19 (1972) 165.
- [16] M.E. Brookfield, The emplacement of giant ophiolite nappes, I. Mesozoic-Cenozoic examples, *Tectonophysics* 37 (1977) 247.
- [17] P. Molnar and P. Tapponnier, Cenozoic tectonics of Asia: effects of a continental collision, *Science* 189 (1975) 419.
- [18] W.C. Pitman III, E.M. Herron and J.R. Heirtzler, Magnetic anomalies in the Pacific and sea floor spreading, *J. Geophys. Res.* 73 (1968) 2069.
- [19] J.R. Heirtzler, G.O. Dickson, E.M. Herron, W.C. Pitman III and X. Le Pichon, Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents, *J. Geophys. Res.* 73 (1968) 2119.
- [20] E.M. Herron, Magnetic lineations in the extreme southeast Pacific and their bearing on the evolution of the Scotia Arc and Patagonia, *Geol. Soc. Am., Abstr. Progr.* 6 (1974) 791.
- [21] P.J. Coney, Cordilleran tectonic transitions and motion of the North American plate, *Nature* 233 (1971) 462.
- [22] H.W. Menard and T. Atwater, Changes in direction of sea floor spreading, *Nature* 219 (1968) 463.
- [23] S. Uyeda and Z. Ben-Arraham, Origin and development of the Philippine Sea, *Nature Phys. Sci.* 240 (1972) 176.
- [24] T.W.C. Hilde, S. Uyeda and L. Kroenke, Evolution of the western Pacific and its margins, in: *Present State of Plate Tectonics*, J. Bonnin and R.S. Dietz, eds. *Tectonophysics* 38 (1977) 145.
- [25] S. Uyeda, Some basic problems in the trench-arc-back arc system, in: *Island Arcs, Deep Sea Trenches and Back-Arc Basins*, M. Talwani and W.C. Pitman III, eds., *Am. Geophys. Union, Maurice Ewing Ser.* 1 (1977) 1.
- [26] D.A. Clague, G.B. Dalrymple and R. Moberly, Petrography and K-Ar ages of dredged volcanic rocks from the western Hawaiian Ridge and the southern Emperor Seamount, *Geol. Soc. Am. Bull.* 86 (1975) 991.
- [27] W.C. Pitman III and M. Talwani, Sea-floor spreading in the North Atlantic, *Geol. Soc. Am. Bull.* 83 (1972) 619.
- [28] E.M. Herron, J.F. Dewey and W.C. Pitman III, Plate tectonics model for the evolution of the Arctic, *Geology* 2 (1974) 377.
- [29] P.R. Vogt, N.A. Ostenson and G.L. Johnson, Magnetic and bathymetric data bearing in sea-floor spreading north of Iceland, *J. Geophys. Res.* 75 (1970) 903.
- [30] M. Mayhew, C.L. Drake and J.F. Nafe, Marine geophysical measurements on the continental margins of Labrador Sea, *Can. J. Earth Sci.* 7 (1970) 199.
- [31] X. Le Pichon, R.D. Hyndman and G. Pautot, Geophysical study of the opening of the Labrador Sea, *J. Geophys. Res.* 76 (1971) 4724.
- [32] P.R. Vogt, O.E. Avery, W.J. Morgan, G.L. Johnson, E.D. Schneider and R.H. Higgs, Morphology, magnetic anomalies and evolution of the northeast Atlantic and Labrador Sea, 3. Evolution, *EOS, Trans. Am. Geophys. Union* 50 (1969) 184 (abstract).
- [33] E.M. Herron and M. Talwani, Magnetic anomalies on the Reykjanes Ridge, *Nature* 238 (1972) 390.
- [34] R.K. Lattimore, P.A. Rona and O.E. DeWald, Magnetic anomaly sequence in the Central North Atlantic, *J. Geophys. Res.* 79 (1974) 1207.
- [35] P.D. Rabinowitz and G.M. Purdy, The Kane fracture zone in the western Central North Atlantic Ocean, *Earth Planet. Sci. Lett.* 33 (1976) 21.
- [36] G.O. Dickson, W.C. Pitman III and J.R. Heirtzler, Magnetic anomalies in the South Atlantic and ocean floor spreading, *J. Geophys. Res.* 73 (1968) 2087.
- [37] A.E. Maxwell, Initial Reports of the Deep Sea Drilling Project III, U.S. Government Printing Office, Washington, D.C. (1970) 806.
- [38] J.W. Ladd, G.P. Dickson and W.C. Pitman III, The age of the South Atlantic, in: *The Ocean Basins and Margins*, 1. The South Atlantic, A.E.M. Nairn and F.G. Stehli.

- eds. (Plenum Press, New York, N.Y., 1973) 555.
- [39] B.T. Malfait and M.G. Dinkelman, Circum-Caribbean tectonic and igneous activity and the evolution of the Caribbean plate, *Geol. Soc. Am. Bull.* 83 (1972) 251.
- [40] R. Weyl, *Die Geologie der Antillen* (Gebr. Borntraeger, Berlin, 1966) 410.
- [41] A.A. Meyerhoff and C.W. Hatten, Diapiric structures in central Cuba, *Am. Assoc. Pet. Geol. Mem.* 8 (1968) 315.
- [42] P.H. Mattson, Middle Cretaceous nappe structures in Puerto Rican ophiolites and their relation to the tectonic history of the Greater Antilles, *Geol. Soc. Am. Bull.* 84 (1973) 21.
- [43] W.H. Monroe, The age of the Puerto Rico Trench, *Geol. Soc. Am. Bull.* 79 (1978) 487.
- [44] K.M. Khudoley and A.A. Meyerhoff, Paleogeography and geological history of the Greater Antilles, *Geol. Soc. Am. Mem.* 129 (1971) 199.
- [45] B.E. Tucholke and J.I. Ewing, Bathymetry and sedimentary structure of the Greater Antilles outer ridge and vicinity, *Geol. Soc. Am. Bull.* 85 (1974) 1789.
- [46] F. Nagle, Geology of the Puerto Plata area, Dominican Republic, relative to the Puerto Rico Trench, in: *Transactions, 5th Caribbean Geological Conference*, St. Thomas, V.I., P.H. Mattson, ed., Queens College Geol. Bull. 5 (1971) 79.
- [47] T.L. Holcombe, P.R. Vogt, J.E. Matthews and R.R. Murchison, Evidence for sea floor spreading in the Cayman Trough, *Earth Planet. Sci. Lett.* 20 (1973) 357.
- [48] B.C. Heezen, M.R. Perfit and M. Dreyfus, The Cayman Ridge, *Geol. Soc. Am., Abstr. Progr.* 5 (1973) 663.
- [49] J.F. Dewey, W.C. Pitman III, W.B.F. Ryan and J. Bonnin, Plate tectonics and the evolution of the Alpine system, *Geol. Soc. Am. Bull.* 84 (1973) 3137.
- [50] G. Boillot and R. Capdevila, The Pyrenees: subduction and collision?, *Earth Planet. Sci. Lett.* 35 (1977) 151.
- [51] K.J. Hsü and S.O. Schlanger, Ultrahelvetic flysch sedimentation and deformation related to plate tectonics, *Geol. Soc. Am. Bull.* 82 (1971) 1207.
- [52] R. Trümpy, Penninic-Austroalpine boundary in the Swiss Alps: a presumed former continental margin and its problems, *Am. J. Sci.* 275-A (1975) 209.
- [53] V.J. Dietrich, Evolution of the Eastern Alps: a plate tectonics working hypothesis, *Geology* 4 (1976) 147.
- [54] R. Lafitte, Les plissements post-nummalitiques dans l'Atlas Saharien, *Bull. Soc. Geol. Fr.* 5 (1939) 135.
- [55] Société Chérifienne des Pétroles, Le Bassin du Sud-Ouest Marocain, in: *Sedimentary Basins of the African Coasts, 1. Atlantic Coast*, D. Reyre, ed. (Assoc. African Geol. Surveys, Paris, 1966) 5.
- [56] R.W. Girdler and P. Styles, Two stage Red Sea floor spreading, *Nature* 247 (1974) 7.
- [57] H.L. Davies and I.E. Smith, Geology of Eastern Papua, *Geol. Soc. Am. Bull.* 82 (1971) 3299.
- [58] J. Avias, Overthrust structure of the main ultrabasic New Caledonian Massives, *Tectonophysics* 4 (1967) 531.
- [59] J.J. Guillon and P. Rothier, Les stades d'évolution et de mise en place des Massifs ultramafiques de Nouvelle Calédonie, *Bull. B.R.G.M.* 2 (1971) 5.
- [60] R.G. Coleman and W.P. Irwin, Ophiolites and ancient continental margins in: *The Geology of Continental Margins*, C.A. Burk and C.L. Drake, eds. (Springer-Verlag, New York, N.Y., 1974) 921.
- [61] R.G. Tysdale, J.E. Case, G.R. Winkler and S.H.B. Clark, Sheeted dikes, gabbro, and pillow basalt in flysch of coastal southern Alaska, *Geology* 5 (1977) 377.
- [62] A. Gansser, Asseralpine ophiolithprobleme, *Eclogae Geol. Helv.* 52 (1959) 659.
- [63] W.G. Ernst, Interpretative synthesis of metamorphism in the Alps, *Geol. Soc. Am. Bull.* 84 (1973) 2053.
- [64] D.P. McKenzie and J.G. Selater, The evolution of the Indian Ocean since the Late Cretaceous, *Geophys. R. Astron. Soc. J.* 25 (1971) 437.
- [65] J.C. Briden, G.E. Drewry and A.G. Smith, Phanerozoic equal-area world maps, *J. Geol.* 82 (1974) 555.