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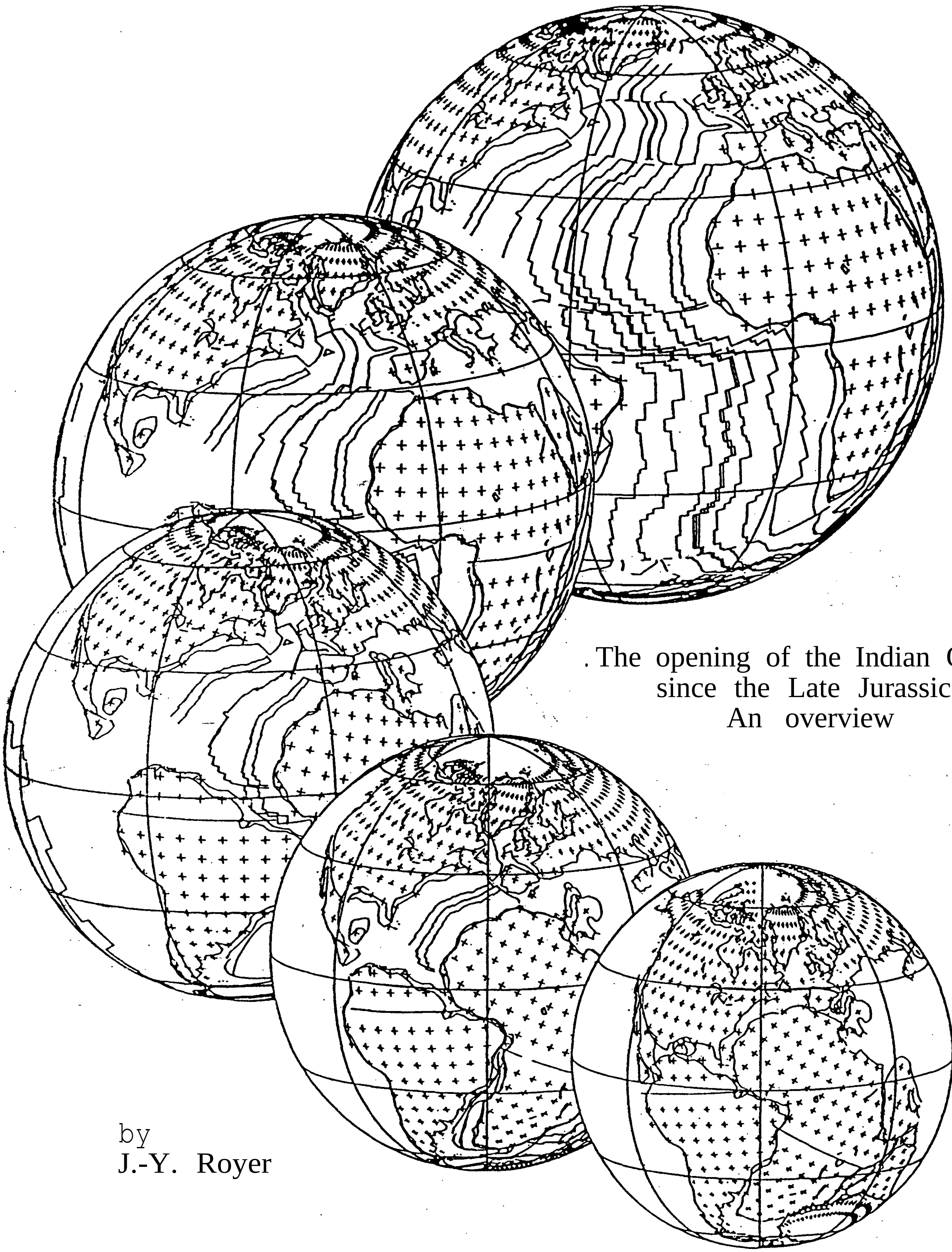

The opening of the Indian Ocean since the Late Jurassic: An overview

by
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Slide 1

THE OPENING OF THE INDIAN OCEAN SINCE THE LATE JURASSIC: AN OVERVIEW

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The Indian Ocean floor (Fig. 1) is characterized by a system of three active spreading ridges that now separates four major fragments of the former super-continent Gondwana: Africa, India, Australia and Antarctica. The northern branch of this ridge system rises in the Gulf of Aden, separating Africa from Arabia, and continues along the Carlsberg Ridge and the Central Indian Ridge which separates Africa from India. At 25°S, 70°E, the Central Indian Ridge intersects the two other branches, the Southwest Indian Ridge that extends between Africa and Antarctica towards the South Atlantic, and the Southeast Indian Ridge that extends towards the South Pacific between Antarctica and India, and Antarctica and Australia. Numerous ridges and plateaus of intermediate depth appear on either sides of the spreading ridges; the extension of some of them such as the Kerguelen Plateau (600 x 2000 km) or the Ninetyeast Ridge (~4000 km long) is quite unique in the world ocean. The size, number and distribution of these elevations have raised many questions about their nature and origin as well as their role in the continuing development of the Indian Ocean. From east to west, they are the South Tasman Rise, the plateaus off western Australia (Naturaliste, Cuvier, Wallaby, Exmouth), Broken Ridge and the Kerguelen Plateau, Ninetyeast Ridge, Chagos-Laccadive Ridge and the Mascarene Plateau, the Chain and Murray Ridges, Madagascar Plateau, Del Cano Rise, Crozet Plateau, Conrad Rise, Gunnerus Ridge, Mozambique Ridge, Astrid Ridge, Agulhas Plateau and finally Maud Rise (Fig. 1). Mapping of the oceanic magnetic anomaly pattern along with sparse Deep Sea Drilling and Ocean Drilling Program core samples have permitted to date most of the Indian Ocean crust (Fig. 2). Fracture zone trends interpreted from satellite altimetry (Seasat and Geosat), bathymetry, seismic, gravity and magnetic data defined the seafloor tectonic fabric Indian Ocean floor. In addition to the topographic features previously described, three extinct spreading systems have been identified, which add to the complexity of the Indian Ocean. The oldest one, located in the western Somali Basin, became extinct in the Early Cretaceous (~ 115 Ma; Ségoufin and Patriat, 1980; Cochran, 1988) and corresponds to the early separation of Madagascar from Africa. A fossil spreading center of Paleocene age (anomalies 31 to 27) has been recognized in the Mascarene Basin (Schlich, 1982) and relates to the separation of Seychelles and India from Madagascar. The youngest extinct spreading system is located in the Wharton Basin where seafloor spreading between India and Australia ceased in the Middle Eocene (Liu et al., 1982; Geller et al., 1983).

Slide 4 This plate kinematic model for the Indian Ocean is based on a data compilation that includes detailed mapping of the fracture zone pattern which record the paleo-spreading directions, and the magnetic anomaly data which date the seafloor. To locate the fracture zones, conventional bathymetric soundings (PDR measurements)
Slides 5, 6 along ship's tracks, and satellite altimeter data (SEASAT, GEOSAT) are jointly analyzed. Short wavelength (20 - 100 km) of satellite derived gravity data are highly correlated with the uncompensated topography of the ocean floor. On this
Slide 7 example taken between Australia and Antarctica, one can precisely chart the fracture
Slide 8 zones that record the relative motions between these two plates since they broke apart. The GEOSAT data which cover the ocean down to 72°S bring a wealth of new information over the poorly charted Southern Ocean (e.g., Haxby, 1987; Mc Adoo and Sandwell, 1988). The combination of the two data sets permit to map
Slide 9 the tectonic fabrics of the ocean floor (here, between Australia and Antarctica). In
Slides 10, 11 addition to this information, analyses of the residual magnetic anomaly data (here in the south western Indian Ocean) provide the age of the ocean floor. The magnetic
Slides 12, 13 anomaly data are interpreted on linear profiles, then they are identified on track chart and finally, the magnetic picks (chrons) are digitized. More than 2500 picks
Slides 14, 15 have been compiled in this study. The crustal ages and seafloor tectonic fabrics are combined to build a detailed tectonic fabric chart of the Indian Ocean floor.

Slide 16 Plate reconstructions are derived by matching conjugate magnetic lineations and paleo-transform fault segments. Techniques involving 3-D interactive computer graphics and least-square best-fitting algorithms are applied to calculate the rotation parameters (finite poles and angles). Closure of triple junctions as well

Slide 17 as ages from ODP or DSDP core samples are used as additional constraints for the reconstructions. This example shows a portion of the tectonic fabric chart between Australia and Antarctica. Magnetic picks on the computer display are color-coded Slide 18 by age (e.g., purple = chron 5, green = chron 6) and fracture zones are color-coded by plate. A reconstruction for chron 6 (21 Ma) is derived by matching Slide 19 simultaneously the conjugate picks and paleo-transform segments corresponding to that chron. The reconstructed magnetic lineations and transform faults define an isochron line (orange line) that is later restored (i.e., rotated back) on the conjugate plates (e.g., the blue lines corresponding to chron 13 (36 Ma) on either side of Slide 20 isochron 6). This plate kinematic model describes the relative motions between the nine Gondwana fragments: Africa, (East) Antarctica, Arabia, Australia, India, Madagascar, Seychelles, Somalia, and Sri Lanka. As a consequence of the plate boundary reorganizations, some oceanic basins (e.g., southern Wharton Basin, eastern Mascarene Basin) and submarine ridges (e.g., northern Kerguelen Plateau) transferred from one plate to another and may have behaved as independent micro-plates for short periods of time.

Slide 21 Plate kinematic reconstructions based on this data compilation (Table 1) show that the evolution of the Indian Ocean after the break-up of Gondwana in the Late Jurassic can be summarized in three main spreading phases, corresponding to three main configurations of the spreading plate boundaries (Table 2). The causes for these ocean-wide plate boundary reorganizations are not yet fully understood. Seafloor spreading initiated in the Late Jurassic after the break-up between East and West Gondwana. The first major reorganization during the Cretaceous Magnetic Quiet Zone is probably linked to the initiation subduction of the Neo-Tethys under Eurasia. The last reorganization in the Middle Eocene follows the collision of the Indian plate with Eurasia.

Slides 22, 23 The three spreading episodes are preceded by a phase of continental extension (Phase 0, Table 2) which started in the Late Triassic/Early Jurassic. The continental extension between east and west Gondwana resulted in a marine Slide 24 incursion between Madagascar and east Africa; the occurrence of massive flood basalts, spanning from 170 to 190 Ma (e.g., White and McKenzie, 1989), in south Africa (Karoo, Lebombo) and Antarctica (Queens Maud Land) evidence the southward progression of continental stretching (Lawver et al., in press). Phase 0 ended by the break-up of Gondwana and initiation of seafloor spreading (Phase 1) at about 160 Ma (chron M25) between east Gondwana (South America, Africa and Arabia) and west Gondwana (Madagascar, Seychelles, India, Antarctica and Australia).

Slides 25, 26 During Phase 1 (Fig. 3, Table 2), Africa separated from Madagascar and Antarctica, creating respectively the western Somali Basin (Ségoufin and Patriat, 1980; Rabinowitz et al., 1983; Coffin and Rabinowitz, 1987; Cochran, 1988), the symmetric Mozambique Basin (Ségoufin, 1978; Simpson et al., 1979) and the basin off Dronning Maud Land, Antarctica (Bergh, 1977, 1987). At about 130 Ma (chron M10, M4), the South Atlantic started to open between South America and Africa (Rabinowitz and LaBrecque, 1979). At about the same time, India separated from Australia and Antarctica, creating the Mesozoic basins along the western margin of Australia (Markl, 1974, 1978; Larson et al., 1979; Veevers et al., 1985).
Slide 27 Seafloor spreading in the Somali Basin between Africa and Madagascar stopped in the Early Cretaceous at 115 Ma (Ségoufin and Patriat, 1980) when the spreading systems between Africa and Antarctica and between India and Antarctica connected. Strike-slip motions between India and Madagascar probably occurred since the break-up of India and Antarctica, which is not yet clearly dated, until India and Madagascar rifted apart in the mid-Cretaceous. By the end of phase one in the mid-
Slide 28 Cretaceous, there was only one active spreading center separating the Africa-Arabia-Madagascar-India block from the Antarctica-Australia block.

Slides 29, 30 Following the break-up of India and Madagascar, and Australia and Antarctica in the mid-Cretaceous, the single plate boundary system of phase 1 reorganized into a five arm spreading system which characterizes phase 2 (Fig. 4, Table 3). The westernmost spreading ridge generated the basins between Africa-
Slide 31 Madagascar and Antarctica (Bergh and Norton, 1976; Patriat, 1979, LaBrecque and Hayes, 1979; Sclater et al., 1981; Fisher and Sclater, 1983). North of the Conrad Rise, this spreading ridge connected with a northern arm between Madagascar and India that created the Madagascar and the Mascarene Basins, and a western arm between Antarctica and India, which generated the mirrored Central Indian Basin and Crozet Basin (McKenzie and Sclater, 1971; Sclater and Fisher, 1974; Schlich, 1975, 1982). The second triple junction was located west of the Kerguelen Plateau where the India/Australia spreading center in the Wharton Basin (Sclater and Fisher, 1974; Liu et al., 1983) connected with the Australia/Antarctica spreading center (Cande and Mutter, 1982). The major event in phase 2 coincides with the

emplacement of the Deccan Traps at about 65 Ma (~chron 31). After chron 31, the spreading center in the Mascarene basin progressively jumped northward of the
Slide 32 Seychelles (Schlich, 1975, 1982), where it generated the eastern Somali Basin and the Arabian Sea (McKenzie and Sclater, 1971; Whitmarsh, 1974; Schlich, 1975, 1982). Also at that time a drastic increase in the spreading rates (5 to 10 cm/yr, half-rates) is observed simultaneously in the Mascarene, Madagascar, Crozet, Wharton and Central Indian basins (McKenzie and Sclater, 1971; Sclater and Fisher, 1974; Schlich, 1975, 1982), whereas a major change in spreading direction is observed along the southwest Indian Ridge (Patriat et al., 1985; Royer et al., 1988). During this phase, seafloor spreading between Australia and Antarctica remained very slow (~ 1cm/yr, Cande and Mutter, 1982). Despite these changes in the spreading regime, the configuration of the spreading centers remained the same
Slide 33 until India collided with Eurasia in the Middle Eocene.

Slides 34, 35 The latest period (Phase 3, Table 3) in the evolution of the Indian Ocean started with a major reorganization of the spreading centers at 43 Ma (chron 18), following the collision of India with Asia. The new configuration of the
Slide 36 spreading ridges corresponds to the present-day ridge system (Fig. 5). Major
Slide 37 changes in the direction and rate of spreading occurred progressively from east to west in the Central Indian Basin, the Crozet Basin, the Madagascar Basin, the eastern Somali Basin and the Arabian Sea (McKenzie and Sclater, 1971; Sclater et al., 1976; Schlich, 1982; Patriat, 1987). The Mascarene Plateau and the Chagos-
Slide 38 Laccadive Ridge separated just before chron 13 (36 Ma; Fig. 5; Fisher et al., 1971; McKenzie and Sclater, 1971; ODP Leg 115 Scientific Shipboard Party, 1987). Seafloor spreading ceased in the Wharton Basin at chron 18/19 (~ 43 Ma; Liu et al., 1983; Geller et al., 1983) at the same time as Broken Ridge and the Kerguelen Plateau rifted apart (ODP Leg 121 Scientific Drilling Party, 1988; Royer and Sandwell, 1989) and the spreading rate in the Australian-Antarctic Basin drastically increased (Cande and Mutter, 1982). During this phase, the Australian-Antarctic Basin (Weissel and Hayes, 1972), the southern Central Indian Basin (Sclater et al., 1976) and the northern Crozet Basin (Schlich, 1975) were created. As a result
Slide 39 from the differences in spreading rates and orientations of the Central Indian Ridge and the Southeast Indian Ridge, the Southwest Indian Ridge propagated rapidly towards the east during phase 3 (Tapscott et al., 1980; Sclater et al., 1981; Patriat, 1987). Although continental extension within the Red Sea, Gulf of Aden and East
Slide 40 African Rift region initiated as early as the Oligocene, seafloor spreading in the

Gulf of Aden only began at chron 5 (11 Ma; Laughton et al., 1970) and
Slide 41 subsequently in the Red Sea (Girdler and Styles, 1974). The latest change in the plate boundaries followed the "hard" collision of the Indian plate with Asia in the Early Miocene. Slab-pull forces along the Indonesian Trench continued to drag the Australian plate to the north while the motion of India was blocked in the Himalayan region. Because of the differential stresses that developed in the equatorial Indian Ocean, the Wharton and Central Indian Basins are buckling and deforming under a N-S compression since 7 Ma (Weissel et al., 1980; Geller et al., 1983; ODP Leg 116 Shipboard Scientific Party). Convergence between India and Australia corresponds to a clockwise rotation of India about a pole located in the Central Indian Basin.

Slides 42, 43 Table 4 summarizes in six steps the evolution of the plate geometry in the Indian Ocean since the Late Jurassic. The simple two plate system that resulted from the break-up of Gondwana evolved into more complex configurations involving three, four, and five different plates moving relative to each other. The present-day geometry involves at least six different plates and four different types of plate boundaries: five spreading ridges: the Sheba Ridge (Somalia/Arabia), the Carlsberg Ridge (Somalia/India), the Central Indian Ridge (Somalia/Australia), the
Slides 44, 45 Southeast Indian Ridge (Antarctica/Australia), and the Southwest Indian Ridge (Somalia+Africa/Antarctica); a strike-slip boundary: the Owen Fracture Zone (Arabia/India); a convergent plate boundary: the diffuse equatorial boundary extending from the Central Indian Ridge to the Indonesian Trench (India/Australia); and a continental rift (Africa/Somalia). This does not include the trench and strike-slip fault system that bounds the Indian Ocean side of Southeast Asia.

Although the age and relationship of the Indian Ocean basins are now fairly well understood (Fig. 6), the age and origin of most of the Indian Ocean submarine ridges and plateaus remain unclear. Based on core samples (DSDP, ODP) and dredges, some of them clearly appear to be hot-spot traces such as the southern Mascarene Plateau and Chagos-Laccadive Ridge (the hot-spot being now located at La Réunion Island), or the Ninetyeast Ridge (Kerguelen hot-spot). Some ridges have gravity signatures typical of oceanic crust, such as the Crozet and southern Madagascar plateaus. Others appear to have formed during plate boundary reorganization such the Conrad Rise (Fig. 4). Others seems to have formed during periods of massive flood basalt formation, such as the northern Mascarene Plateau, contemporaneous to the Deccan Traps, or the Kerguelen Plateau and Broken Ridge. The nature of all the plateaus bordering the continental margins are still debated, whether they are continental fragments or oceanic features (e.g. Naturaliste Plateau, Mozambique Ridge, Agulhas Plateau, Northern Madagascar Plateau). Future works in the Indian Ocean will focus on these ridges, on the early opening history between Indian and Antarctica, and on constructing a detailed isochron chart of the Indian Ocean floor.

Acknowledgments

Slide 46 This work is part of a joint cooperative programme between the Institut de Physique du Globe de Strasbourg (EOPGS), the Institute for Geophysics University of Texas at Austin (UTIG), the Lamont Doherty Geological Observatory (LDGO), and the Scripps Institution of Oceanography (SIO), aiming at a compilation of most of the bathymetric, gravity, and magnetic data collected in the Indian Ocean. Participating institutions also include the Bernard Price Institute for Geophysics (BPI, South Africa), the Bureau of Mineral Resources (BMR, Australia), and the Institut de Physique du Globe de Paris (IPGP).

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General readings about the evolution of the Indian Ocean:

This is a selection of synthesis papers, some of them recent, that show how ideas have evolved with regard to the evolution of the Indian Ocean and present different views on some aspects of its evolution.

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Figure captions

Figure 1: Bathymetric chart of the Indian Ocean redrawn after the GEBCO chart series (from Royer et al., 1989).

Figure 2: Tectonic summary chart of the Indian Ocean (from Royer et al., 1989).

Figure 3: Plate boundary configuration after the break-up of Gondwana (Phase 1). At chron M21 (150 Ma), seafloor spreading was occurring in the western Somali Basin (Africa/Madagascar) and in the Mozambique channel (Africa/Antarctica). At that time, the Weddell Sea area was the site of predominant strike-slip motion (South America/Antarctica).

Figure 4: Plate boundary configuration after the break-up of India and Madagascar, and Australia and Antarctica in the mid-Cretaceous (~95 Ma). Five different spreading centers were simultaneously active during phase 2.

Figure 5: Plate boundary configuration after the collision of India with Eurasia in the Middle Eocene (~45 Ma). Abandoned spreading centers are also shown. The youngest one is located in the Wharton Basin (east of the Ninetyeast Ridge) and corresponds to the demise of seafloor spreading in the Wharton Basin and the break-up of Broken Ridge and Kerguelen Plateau and to an important increase of spreading rates between Australia and Antarctica at chron 18 time (43 Ma). Another extinct spreading centers is found in the Mascarene Basin where seafloor spreading progressively stopped in the Paleocene (during phase 2) to resume north of the Seychelles and Mascarene Plateau. The oldest extinct spreading center is located in the western Somali Basin and stopped spreading at 115 Ma when the African-Antarctic ridge connected with the Indian-Antarctic ridge (during phase 1).

Figure 6: Present-day map of the Indian Ocean showing the amount of crust generated during the three spreading phases (bold numbers).

Slide legends

Slide 1: Text

Slide 2: General topographic chart of the Indian Ocean (orthographic projection) from Heirtzler and Edwards (1985).

Slide 3: Same view as slide 2 showing the main tectonic features of the Indian Ocean: the active spreading ridge system is outlined by a continuous red-orange line; trenches as the Sunda-Java Trench are shown in yellow; the dotted pattern in the equatorial Indian Ocean outlines the extent of the diffuse plate boundary between the Indian and Australian plate; extinct spreading ridges are shown by a succession of blue (transform faults) and red (extinct spreading center) segments (e.g., in the western Somali Basin, the Mascarene Basin and the Wharton Basin); submarine plateaus and ridges are outlined by green lines with a different tone every 1000 meters; color-coded continents are outlined by their coastlines, the continental shelf-break and five degree tick marks; the white dashed line represents the Equator.

Slide 4: Text

Slide 5: General topographic chart of the Indian Ocean (Mercator projection) from Heirtzler and Edwards (1985).

Slide 6: Residual gravity field of the Atlantic and Indian Ocean (after Haxby, 1987).

Slide 7: Topographic chart of the eastern Indian Ocean and southwestern Pacific Ocean (Mercator projection) from Heirtzler and Edwards (1985).

Slide 8: Vertical deflection profiles plotted at right angle to ascending GEOSAT ground tracks (vertical deflection is the first along track derivative of the geoid data). From this dense set of profiles, one can precisely mapped the Tasman and Balleny fracture zones that record the relative motions of Australia and Antarctica since the time of their break-up in the mid-Cretaceous. In addition, the vertical deflection data clearly outline the Antarctic continental shelf break and particularly a wide basin off George V Land (after Royer and Sandwell, 1989).

Slide 9: Tectonic fabrics of the Australian-Antarctic Basin based on the satellite-derived gravity data. Charted fracture zones have been digitized and displayed on a color computer screen (dark yellow lines). Same legend as Slide 4.

Slide 10: Topographic chart of the south western Indian Ocean (Mercator projection) from Heirtzler and Edwards (1985).

Slide 11: Residual magnetic anomaly profiles from the southern flank of the Southwest Indian Ridge (Slide 10) are plotted at right angle to ship's tracks. The southwest Indian Ridge is located at the top (orange letters). From Royer et al. (1988).

Slide 12: Interpretation of the residual magnetic anomaly profiles shown in Slide 11. Synthetics are on the bottom of the slide. From Royer et al. (1988).

Slide 13: The identified magnetic picks are digitized (dots in the slide) and color-coded by age. One can see conjugate sets of magnetic picks on either side of the Southwest Indian Ridge. Same legend as Slide 4.

Slide 14: More than 2500 magnetic picks from 32 different chrons have been compiled in this study. Same legend as Slide 4.

Slide 15: Tectonic fabric (fracture zones) identified from the satellite altimeter data (to be compared with Slide 6). Some areas such as the Arabian Sea lack identifiable large offset fracture zones; in other areas such as the Central Indian Basin, fracture zones are difficult to chart because of the small obliqueness of the fracture zones (~N0°) relative to the satellite profiles (±20° from North); finally, in old basins where the sedimentary cover is important (e.g., western Somali Basin) the fracture zones do not show in the altimeter data.

Slide 16: Text.

Slide 17: Tectonic fabric chart of the Australian-Antarctic Basin where information from Slides 14 and 15 are combined.

Slide 18: Reconstruction at chron 6 (21 Ma) matching the conjugate magnetic picks (green dots) and paleo-transform segments. Reconstructions are performed either on a 3-D computer display (as on this slide) or by using least-square minimization of the fit for a selected data set (including magnetic picks and fracture zone crossings from the two conjugate plates)

Slide 19: The reconstructed magnetic picks and paleo-transform segments define an isochron for chron 6 (orange line). The isochrons are then restored on the conjugate plates; the blue lines on either sides of isochron 6 correspond to isochron 13 (36 Ma)

Slide 20: Text.

Slide 21: Text.

Slide 22: Text: Main events of pre-breakup Phase 0.

Slide 23: Reconstruction of Gondwana at 240 Ma (Middle Triassic). This view of Gondwana is a polar projection centered on East Antarctica (fixed in its present-day coordinates), with present-day coastlines and grid marks (from Lawver et al., in press).

Slide 24: Pre-break-up configuration of Gondwana at 200 Ma (Early Jurassic) allowing for a marine incursion between Africa and Madagascar. Same projection as Slide 23.

Slide 25: Text: Main events of seafloor spreading Phase 1.

Slide 26: Reconstruction at magnetic magnetic chron M21 (150 Ma, Late Jurassic). Seafloor spreading takes place in the Somali Basin and Mozambique Basin. There are strike-slip motions between the Mozambique Plateau and the Explora escarpment (Antarctica). The plate boundary configuration in the Weddell Sea is not yet clearly known.

Slide 27: Reconstruction at magnetic magnetic chron M0 (119 Ma, Early Cretaceous). Seafloor spreading has started just after magnetic chron M10 (131 Ma) along the western margins of Australia and propagated westward between India and Antarctica. The spreading ridge in the Somali Basin stopped at 115 Ma, probably when the India/Antarctica spreading ridge connected with the Africa/Antarctica spreading system.

Slide 28: Tentative reconstruction at 95 Ma (mid-Cretaceous), during the Cretaceous Magnetic Quiet Zone (C.Q.Z.). At the end of phase one, there is only one active spreading system in the Indian Ocean separating an Africa-Madagascar-Seychelles-India block from an Antarctica-Australia block. Most of the Kerguelen-Broken Plateau was already emplaced at this time, between India and Antarctica.

Slide 29: Text: Main events of seafloor spreading Phase 2.

Slide 30: Close-up of the reconstruction at 95 Ma (Cenomanian).

Slide 31: Reconstruction at magnetic chron 34 (84 Ma, Late Cretaceous, Santonian). The one-arm spreading system of phase 1 (Slide 30) has evolved into a five-arm spreading system with two triple junctions. The first one between the Africa-Madagascar, India-Seychelles, and Antarctic plates is located in the vicinity of the Conrad Rise which probably built during the plate boundary reorganization. The second triple triple junction was located in the vicinity of the Kerguelen-Broken plateau. It is not yet clearly established how the slow spreading Australian-Antarctic ridge connected with the two other ridges.

Slide 32: Reconstruction at magnetic chron 31 (69 Ma, Early Paleocene). India takes off for its rapid northward drift towards Eurasia (linked to the subduction of the Neo-Thetian spreading ridge beneath Eurasia?). The spreading ridge in the Mascarene Basin starts to progressively jump north of the Seychelles block.

Slide 33: Reconstruction at magnetic chron 21 (50 Ma, Middle Eocene) at about the same time as the collision of India with Eurasia, marking the end of spreading Phase 1. The Ninetyeast Ridge built up on the edge of the Indian Plate as it was drifting northward above the Kerguelen-Ninetyeast hotspot. Similarly, the Chagos-Laccadive Ridge built up over the Reunion hotspot.

Slide 34: Text: Main events of seafloor spreading Phase 3.

Slide 35: Plate boundary configuration at the end of Phase 2.

Slide 36: Reconstruction at magnetic chron 18 (43 Ma, Middle Eocene). There are major changes in the rates and directions of spreading along the three Indian Ocean ridges.

Slide 37: Close-up of the reconstruction at magnetic chron 18 (43 Ma). The demise of seafloor spreading in the Wharton Basin, between India and Australia, coincides with the break-up of Broken Ridge and Kerguelen Plateau, and a sharp increase in the spreading rate in the Australian-Antarctic Basin.

Slide 38: Reconstruction at magnetic anomaly 13 (36 Ma, Early Oligocene). The Central Indian Ridge spreads through the Chagos-Laccadive-Mascarene Plateau. The plate boundaries have reached to their present-day configuration.

Slide 39: Reconstruction at magnetic anomaly 6 (21 Ma, Early Miocene). This is the time of the major phase of uplift of the Himalayas. The blocked motion of India towards the north along the slab pull forces that applies to Australia along the Sunda-Java Trench will induce an important deformation in the Central Indian Basin.

Slide 40: Reconstruction at magnetic anomaly 5 (10 Ma, Late Miocene). Seafloor spreading has started in the Gulf of Aden and propagates into the Red Sea.

Slide 41: Present-day isochron chart of the Indian Ocean.

Slide 42: Text: Summary of the four major Phases in the evolution of the Indian Ocean.

Slide 43: Text: Summary of the changes in the plate geometry during the three seafloor spreading phases. The two plate system in the Late Jurassic evolved into the present-day five plate system. In the future, the Somali-Madagascar-Seychelles block may drift away from the African plate as the East African Rift system evolves into a seafloor spreading ridge.

Slide 44: The present-day plate boundary configuration includes five spreading ridges (the Southwest, Southeast, and Central Indian ridges, the Carlsberg Ridge, the Sheba Ridge), a trench (the Sunda-Java Trench), a diffuse plate boundary in the Central Indian Ocean, and a transform boundary (the Owen Fracture Zone-Owen Ridge-Murray Ridge system).

Slide 45: Same legend as Slide 45.

Slide 46: See acknowledgment section.

DATA COMPILATION:	
FRACTURE ZONES:	BATHYMETRY SATELLITE ALTIMETRY
MAGNETIC ANOMALIES:	MORE THAN 2500 PICKS 32 MAGNETIC REVERSALS

PLATE TECTONIC RECONSTRUCTIONS:	
Constraints:	Magnetic anomalies Fracture zones Closure of triple juntion Ages of submarine ridges and plateaus (DSDP, ODP)
Methods:	best-fitting techniques matching conjugate magnetic picks and paleo-transforms 3-D interactive computer graphics

Table 1

4 phases

Phase 0:	240 to 160 Ma
Phase 1:	160 to ~ 95 Ma
Phase 2:	~ 95 to 43 Ma
Phase 3:	43 to 0 Ma

3 plate boundary configurations

Late Jurassic	Break-up of east and west Gondwanaland
Albian-Aptian	Subduction of Neo-Tethys begins (?)
Middle Eocene	Collision of India with Eurasia

Phase 0

AGE	MAIN PRE-BREAK-UP EVENTS
Late Triassic	Marine incursion between Madagascar and east Africa
~ 200 Ma	Opening of the Anza Trough between Kenya and Somalia
175-190 Ma	Intrusion of Karoo flood basalt in South Africa (Karoo, Lebombo) and Antarctica (Queen Maud Land, Transantarctic Mountains)
Late Jurassic	Formation of the Mozambique Ridge and Explora Escarpment

Phase 1

AGE	CHRON	MAIN EVENTS
~ 160 Ma		**Break-up between east and west Gondwanaland**
157 Ma	M25	Tibet separates from NW Australia (Argo Abyssal Plain)
~ 130 Ma	M10-M4	Initiation of spreading in the South Atlantic
~ 126 Ma	M4	Initiation of spreading between India and Australia/Antarctica
115 Ma		Seafloor spreading stops in the Somali Basin (Madagascar/India)

Table 2

Phase 2

AGE	CHRON	MAIN EVENTS
~ 95 Ma		**1st plate boundary reorganization** Break-up between Australia and Antarctica Break-up between India and Madagascar
69 - 65 Ma	31-28	India accelerates towards Eurasia Seafloor spreading stops in the Mascarene Basin Emplacement of the Deccan Traps Important change of motion along the Southwest Indian Ridge Ridge jumps and slow-down of spreading in the South Atlantic
56 Ma	24	India starts to slow down
~ 45 Ma	21	Collision of India with Asia

Phase 3

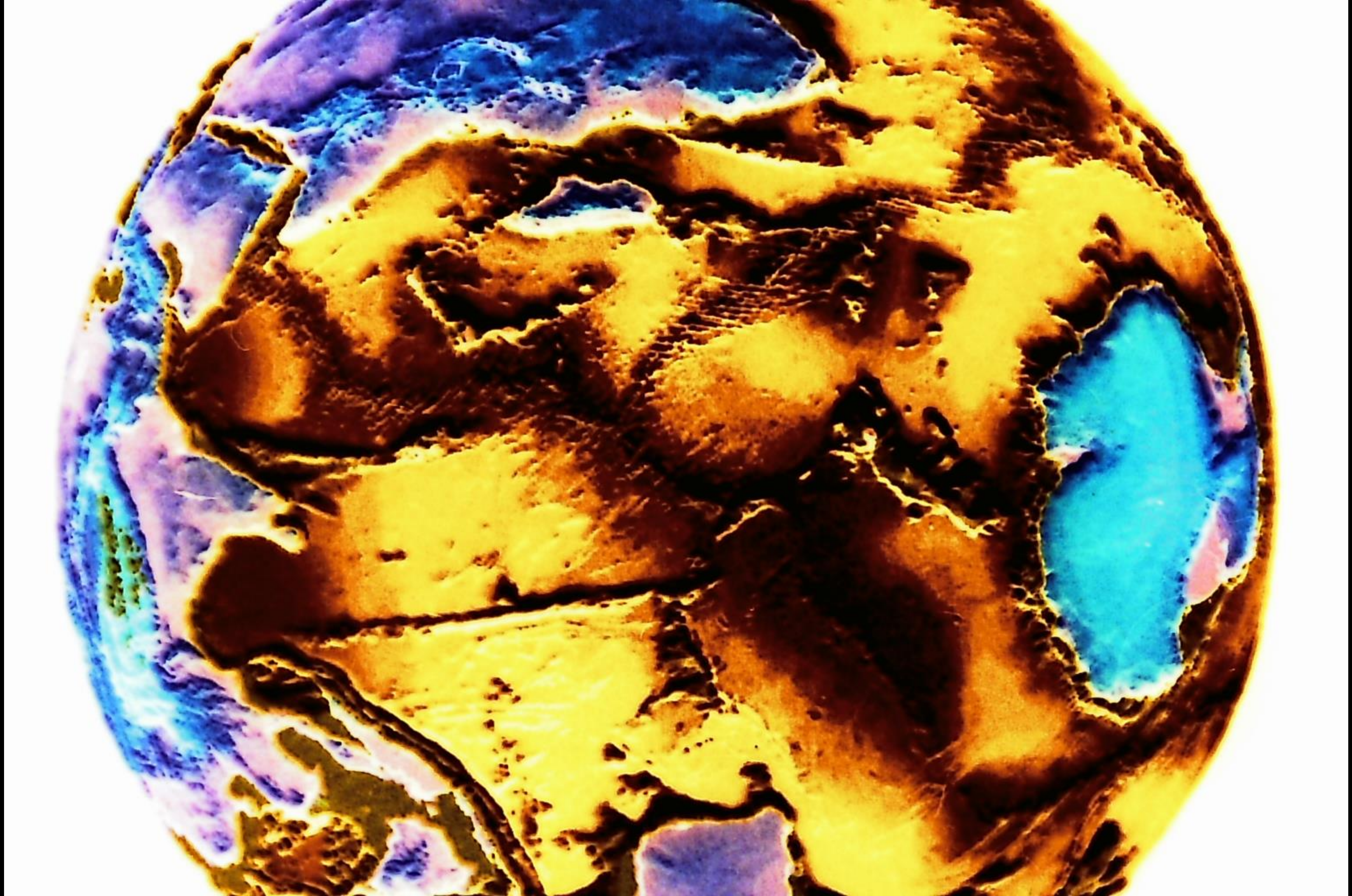
AGE	CHRON	MAIN EVENTS
43 Ma	**18**	**2nd plate boundary reorganization** Demise of spreading in the Wharton Basin (India/Australia) Break-up of Kerguelen plateau and Broken Ridge Major change in the direction and rate of spreading along the Central and Southeast Indian Ridges
38 Ma	15	Break-up of Chagos-Laccadive Ridge and Mascarene Plateau
Oligocene	10	Initiation of stretching in the Red Sea, the east African Rift, anf the Gulf of Aden
Early Miocene	6	Major phase of uplift of the Himalayas
~ 15 Ma	5B	Opening of the Andaman Sea
~ 11 Ma	~5	Initiation of seafloor spreading in the Gulf of Aden
Late Miocene	4	Deformation of the Central Indian Basin

Table 3

EVOLUTION OF THE PLATE GEOMETRY

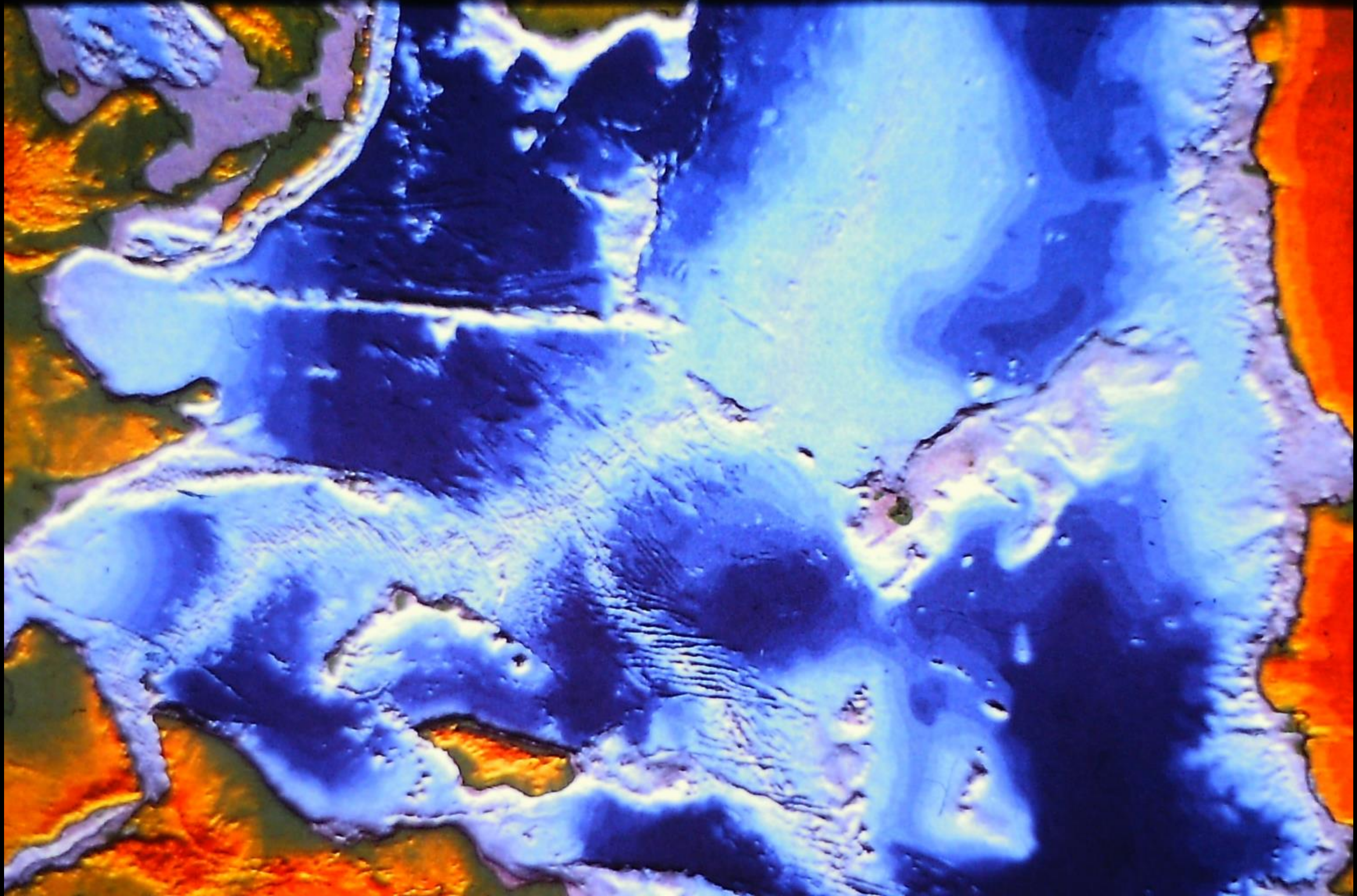
160 - 126	126 - 95	95 - 65	65 - 43	43 - 10	10-present
AFR SOM ARA SAM	AFR SOM ARA	AFR SOM ARA MAD	AFR SOM ARA MAD SEY	AFR SOM ARA MAD SEY	AFR
MAD IND SRI SEY AUS E ANT	MAD SEY	SEY IND SRI	IND SRI	IND SRI AUS	SOM MAD SEY
	IND	AUS	AUS	E ANT	ARA
	SRI	E ANT	E ANT		IND SRI
	AUS E ANT				AUS
					E ANT

The Opening of the INDIAN OCEAN since the LATE JURASSIC

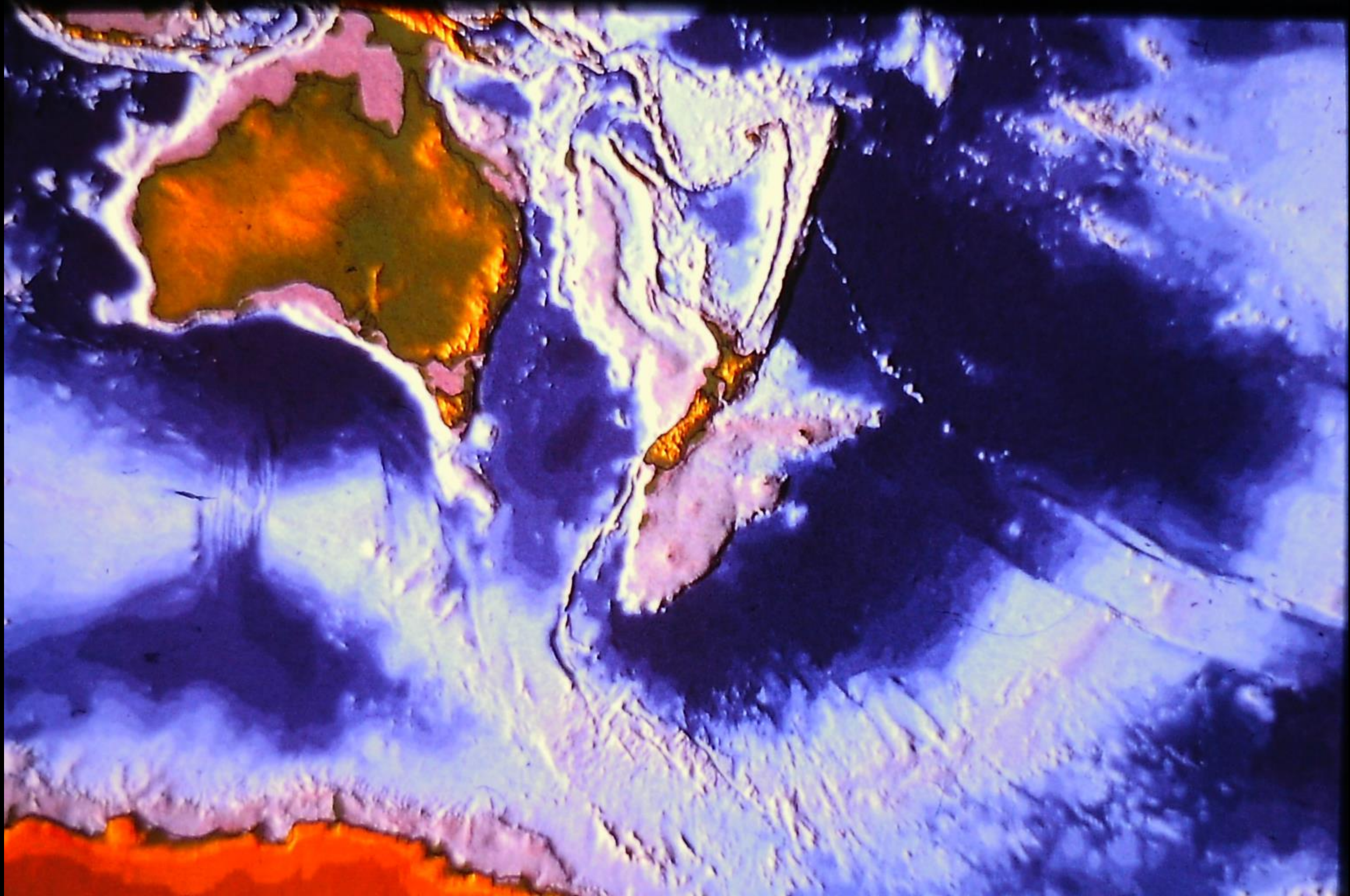


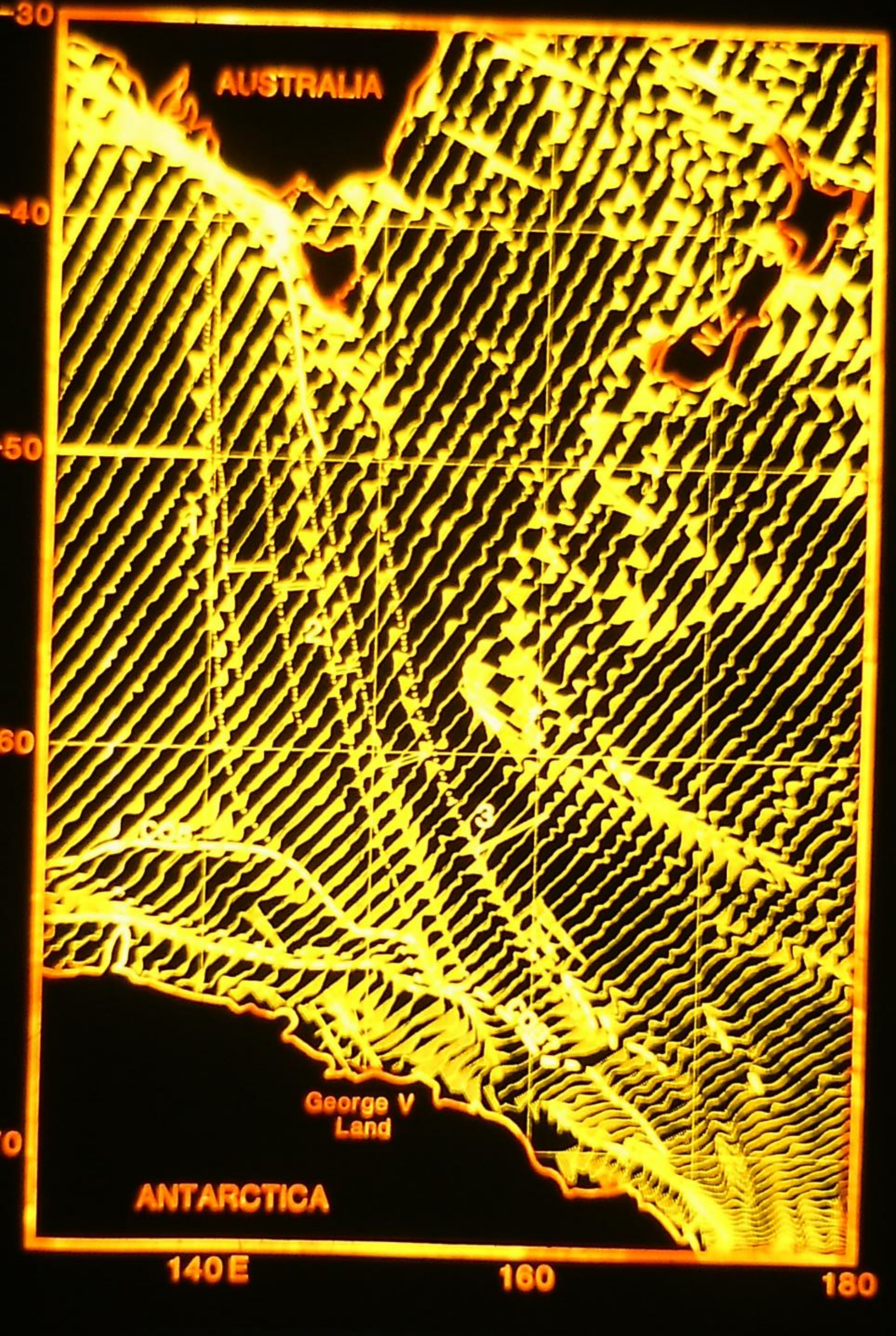
DATA COMPILATION:

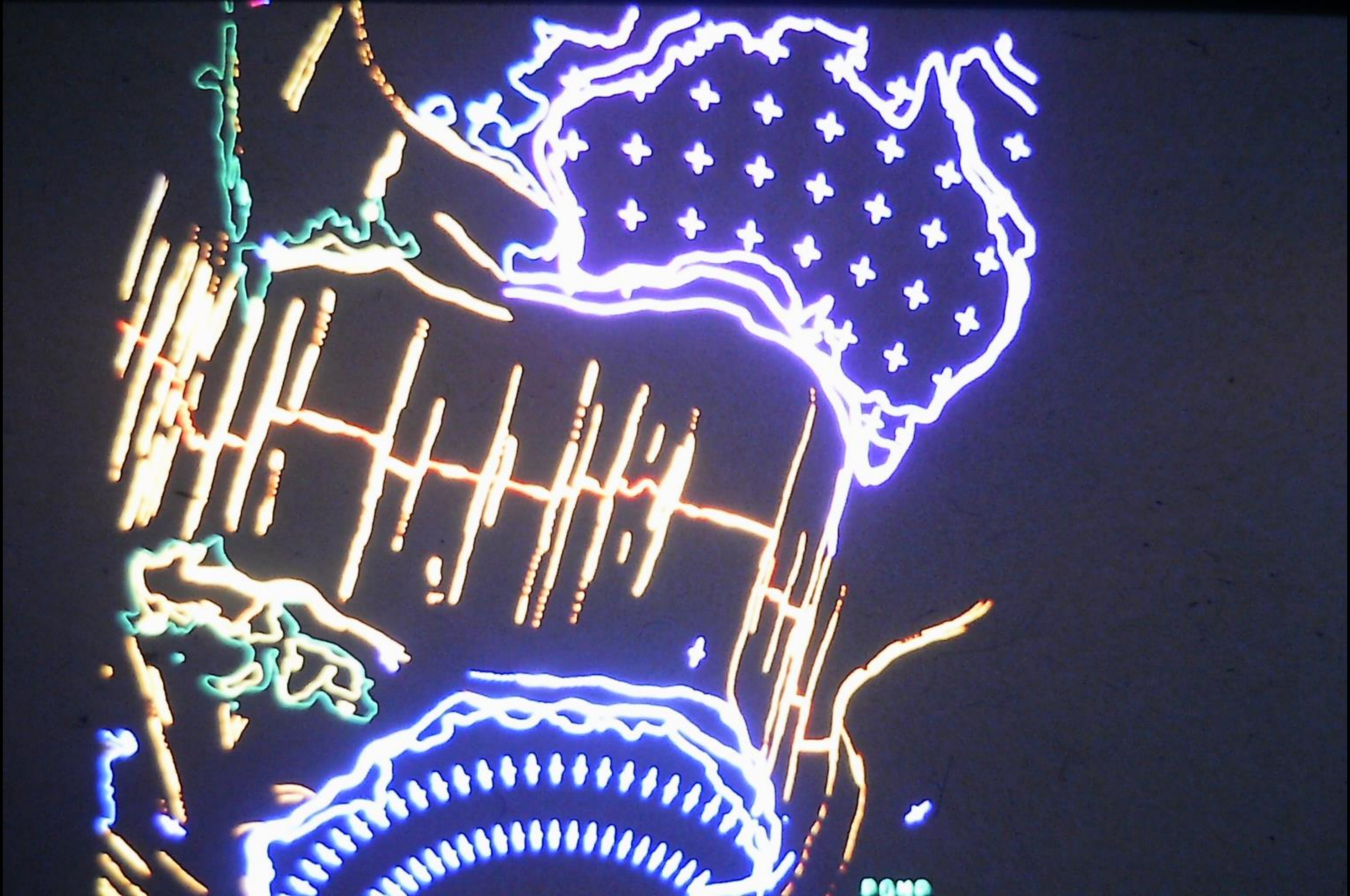
FRACTURE ZONES:	BATHYMETRY SATELLITE ALTIMETRY
MAGNETIC ANOMALIES:	MORE THAN 2500 PICKS 32 MAGNETIC REVERSALS

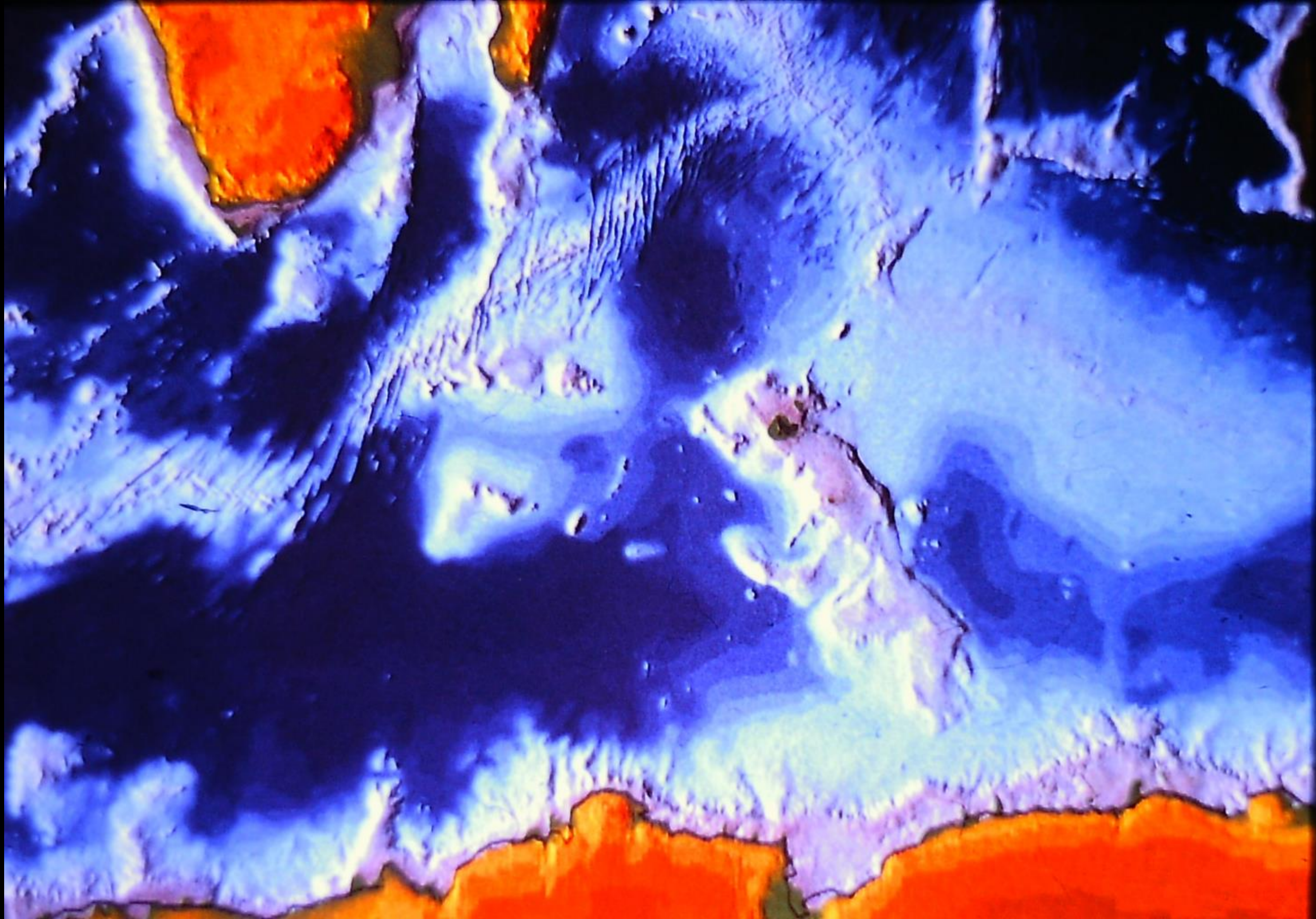



HAXBY, 1987

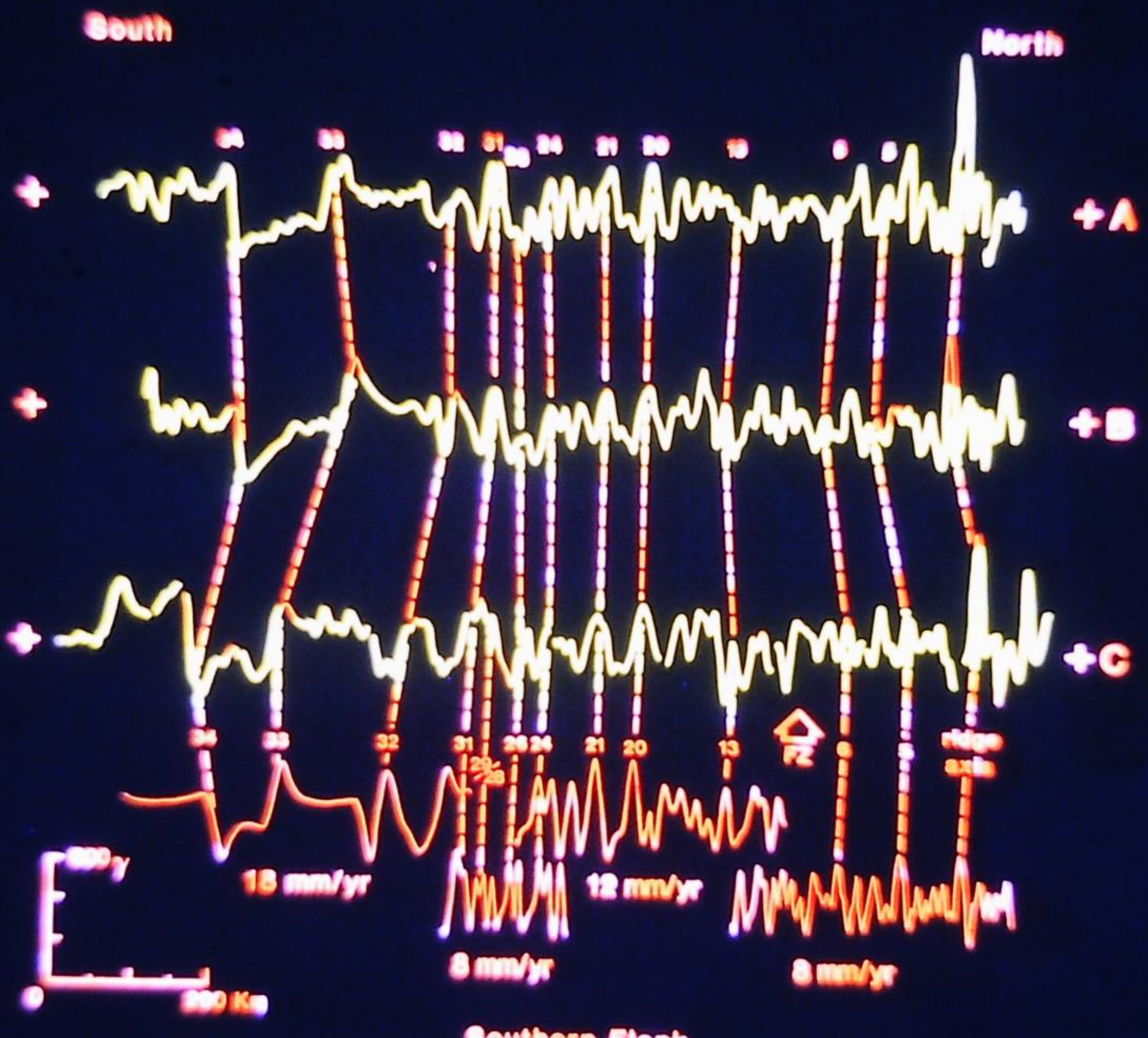



AUSTRALIA
NZ
1
2
3
George V
Land
ANTARCTICA
-30
-40
-50
-60
-70
140E
160
180





+500
0
-500
ship's track

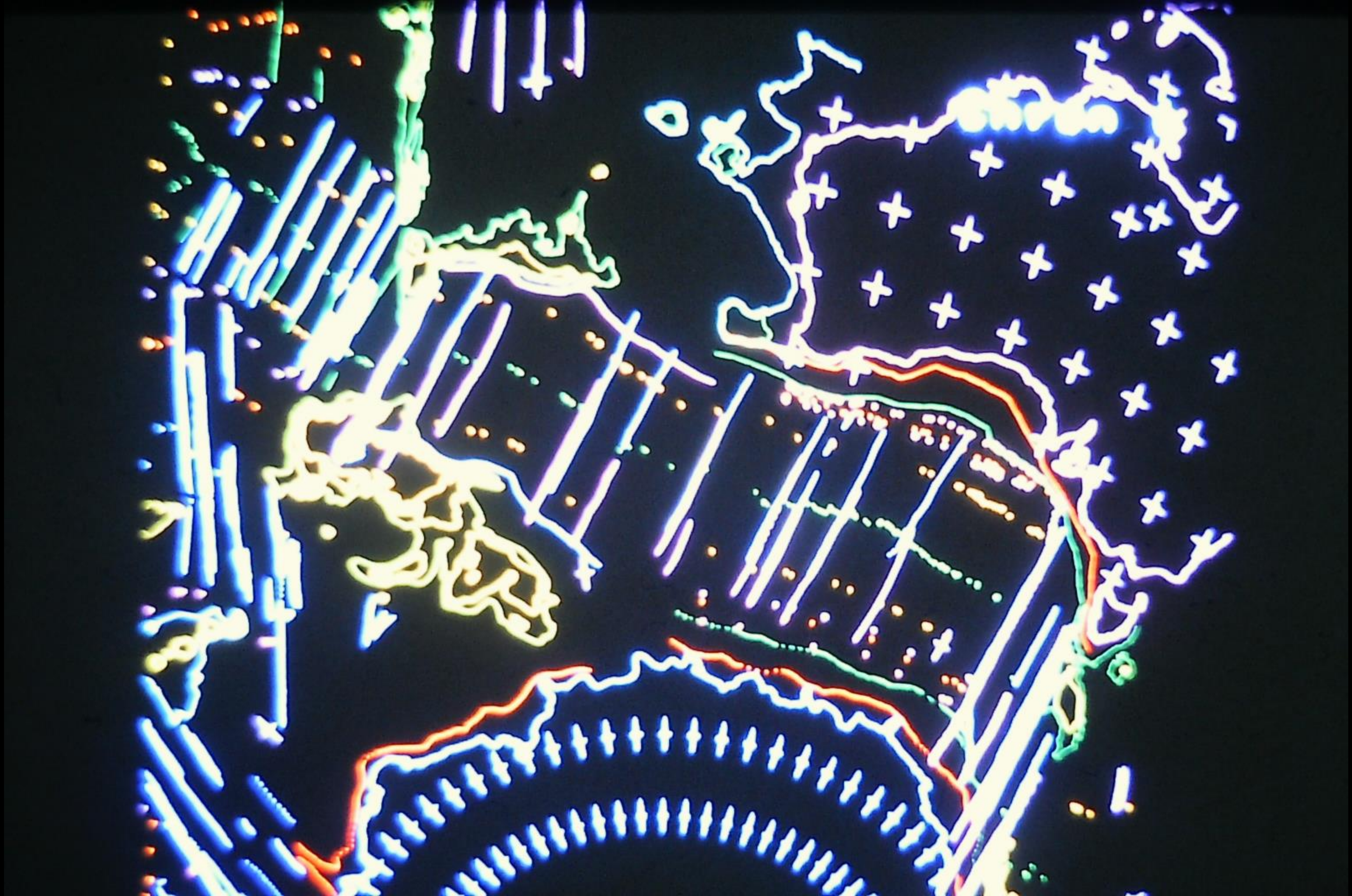


South
North
+A
+B
+C
32
31
21
20
13
21
20
13
FZ
ridge
axis
12 mm/yr
8 mm/yr
8 mm/yr
0

PLATE TECTONIC RECONSTRUCTIONS:

Constraints:
- Magnetic anomalies
- Fracture zones
- Closure of triple juntion
- Ages of submarine ridges and plateaus (DSDP, ODP)

Methods:
- best-fitting techniques matching conjugate magnetic picks and paleo-transforms
- 3-D interactive computer graphics



THIS MODEL INCLUDES 9 DIFFERENT PLATES:

AFR	AFRICA
SOM	SOMALIA
ARA	ARABIA
IND	INDIA
SRI	SRI LANKA
MAD	MADAGASCAR
SEY	SEYCHELLES
AUS	AUSTRALIA
E ANT	EAST ANTARCTICA

In addition, large portions of oceanic crust transferred from one plate to another during plate boundary reoganizations:

eastern Mascarene Basin	SEY/IND -> AFR
southern Central Indian Basin	IND -> IND/AUS -> AUS
crust west of the Ninetyeast Ridge	ANT -> IND
northern Kerguelen Plateau	AUS -> ANT

4 phases

Phase 0:	240 to 160 Ma
Phase 1:	160 to ~ 96 Ma
Phase 2:	~ 96 to 43 Ma
Phase 3:	43 to 0 Ma

3 plate boundary configurations

Late Jurassic	Break-up of east and west Gondwanaland
Albian-Aptian	Subduction of Neo-Tethys begins
Middle Eocene	Collision of India with Eurasia

Phase 0

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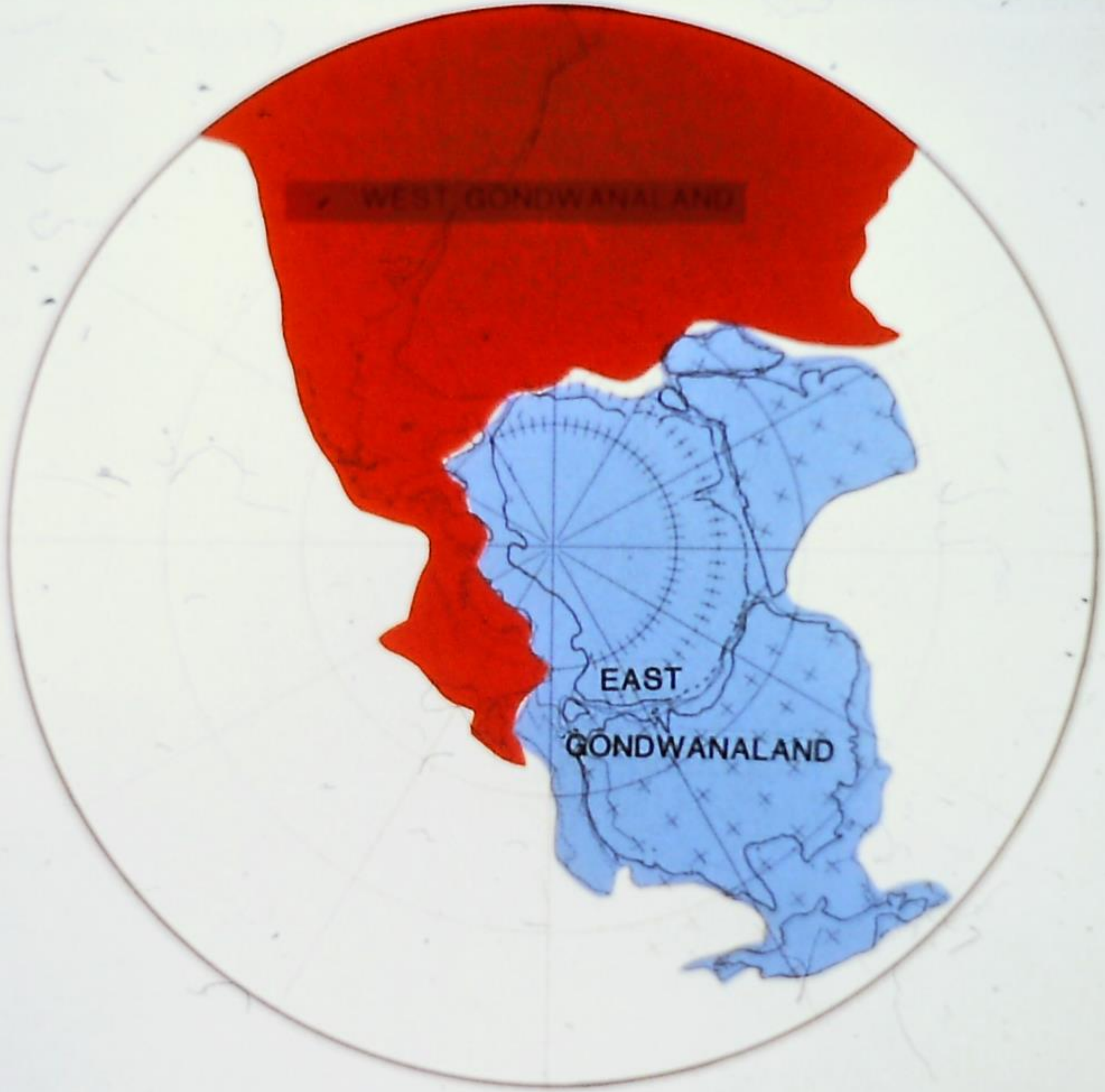
175 Ma	Intrusion of Karoo flood basalt in South Africa (Karoo, Lebombo) and Antarctica (Queen Maud Land, Transantarctic Mountains)
Late Jurassic	Formation of the Mozambique Ridge and Explora Escarpment


GONDWANALAND


WEST GONDWANALAND
EAST
GONDWANALAND

Phase 1

AGE	CHRON	MAIN EVENTS
~ 160 Ma		Break-up between east and west Gondwanaland
157 Ma	M25	Tibet separates from NW Australia (Argo Abyssal Plain)
~ 130 Ma	M10-M4	Initiation of spreading in the South Atlantic
~ 126 Ma	M4	Initiation of spreading between India and Australia/Antarctica
115 Ma		Seafloor spreading stops in the Somali Basin (Madagascar/India)


Chron M21 · 150 Ma
POMP


Chron M0 - 119 Ma
POMP

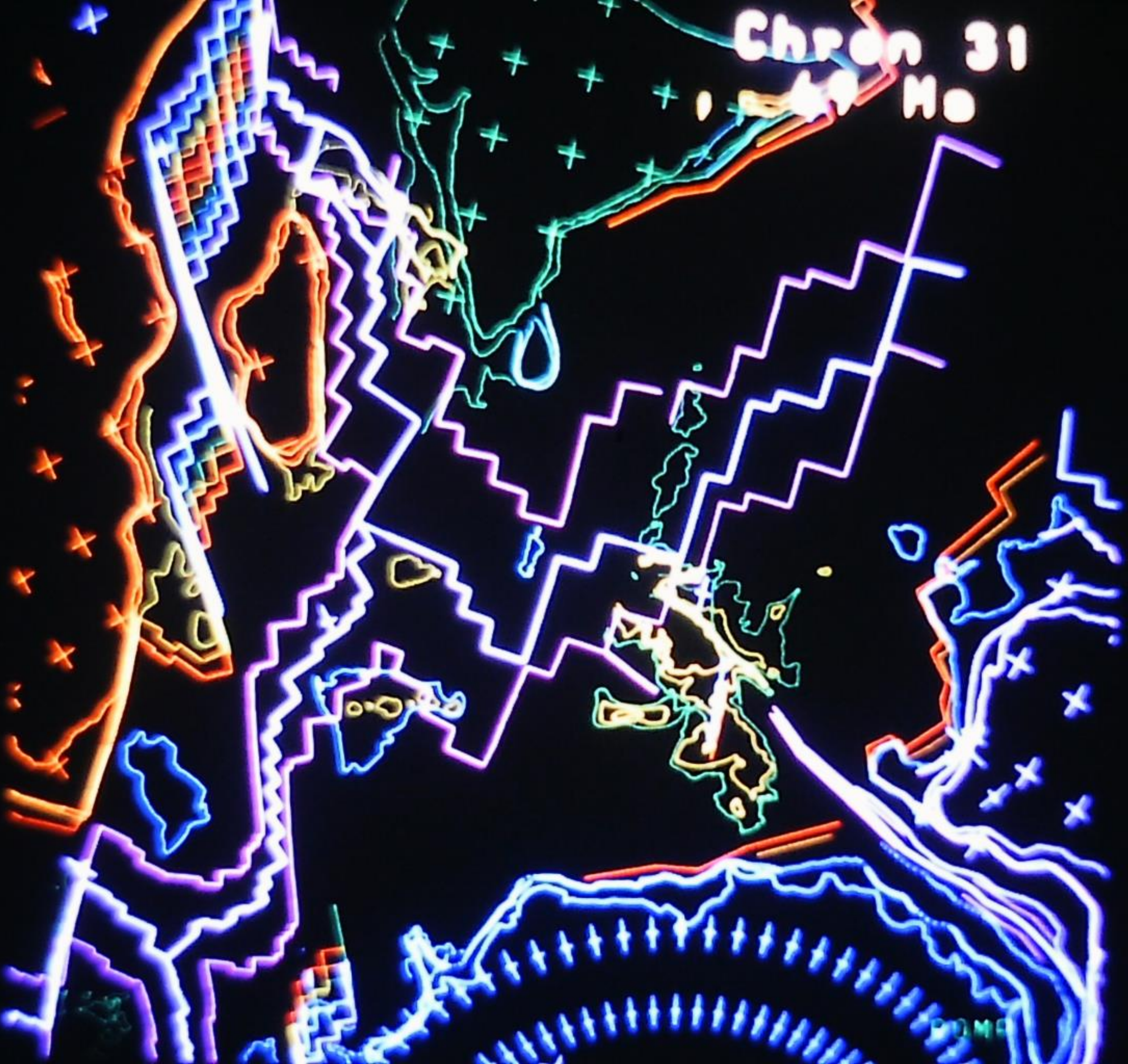
C.Q.Z. - 95 Ma
POMP

Phase 2

Age	Chron	Main events
~ 96 Ma		1st plate boundary reorganization
		Break-up between Australia and Antarctica
		Break-up between India and Madagascar
69 - 65 Ma	31-28	India accelerates towards Eurasia
		Seafloor spreading stops in the Mascarene Basin
		Emplacement of the Deccan Traps
		Important change of motion along the Southwest Indian Ridge
		Ridge jumps and slow-down of spreading in the South Atlantic
56 Ma	24	India starts to slow down
~45 Ma	21	Collision of India with Asia


Cretaceous
Quiet Zone - 95 Ma


Chron 34 - 84 Ma


Chron 31
Ma


Chron 21
50 Mb

Phase 3

Age	Chron	Main events
43 Ma	18	2nd plate boundary reorganization Demise of spreading in the Wharton Basin (India/Australia) Break-up of Kerguelen plateau and Broken Ridge Major change in the direction and rate of spreading along the Central and Southeast Indian Ridges
38 Ma	15	Break-up of Chagos-Laccadive Ridge and Mascarene Plateau
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Late Miocene	4	Deformation of the Central Indian Basin


Chron 21
50 Ma


Chron 18
43 Ma


Chron 18
43 Ma


Chron 13
36 Ma


hron 6
21 Ma


Chron 5
10 Ma


Present-Day
POMP

4 phases

Phase 0:	240 to 160 Ma
Phase 1:	160 to ~ 96 Ma
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3 plate boundary configurations

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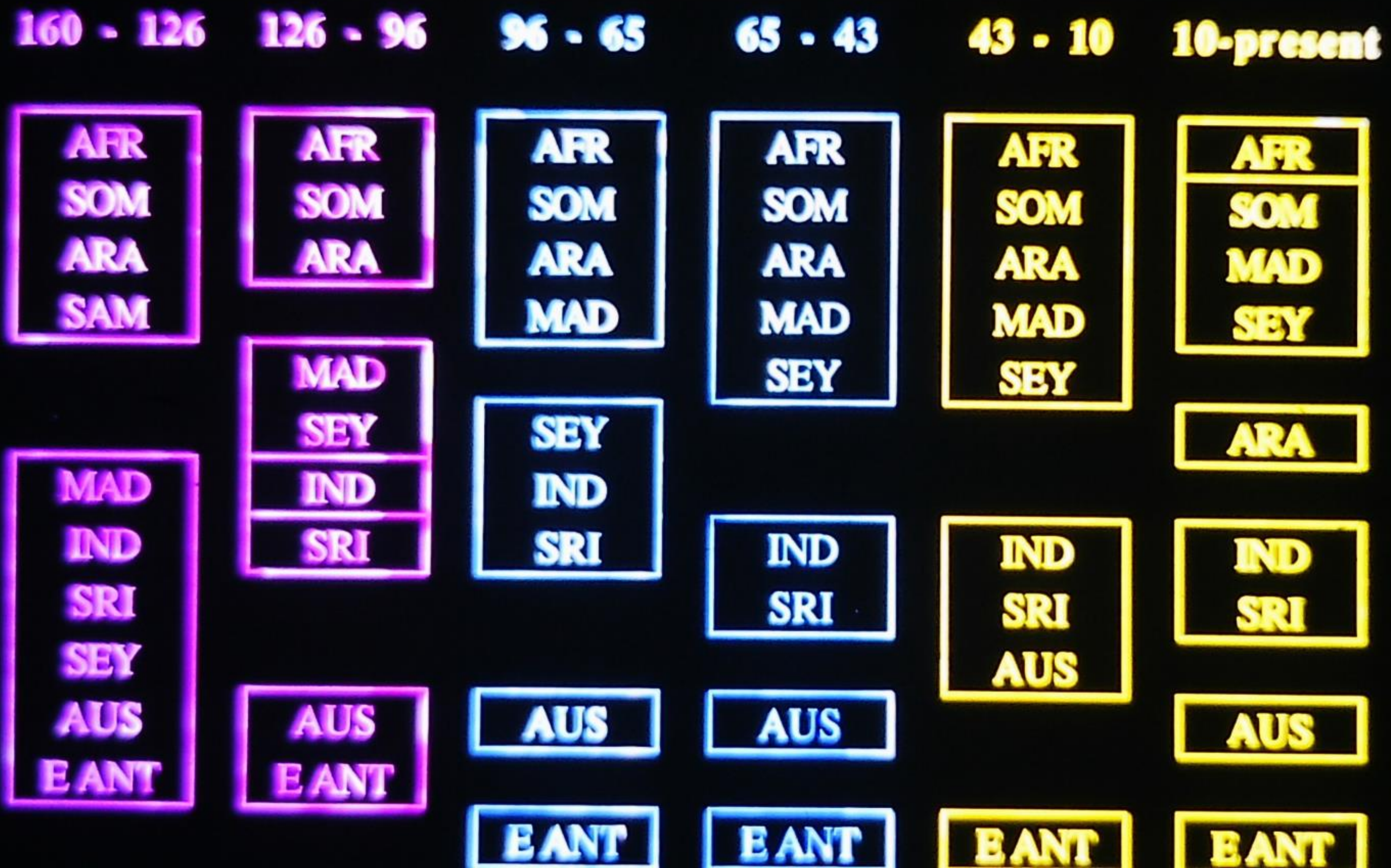
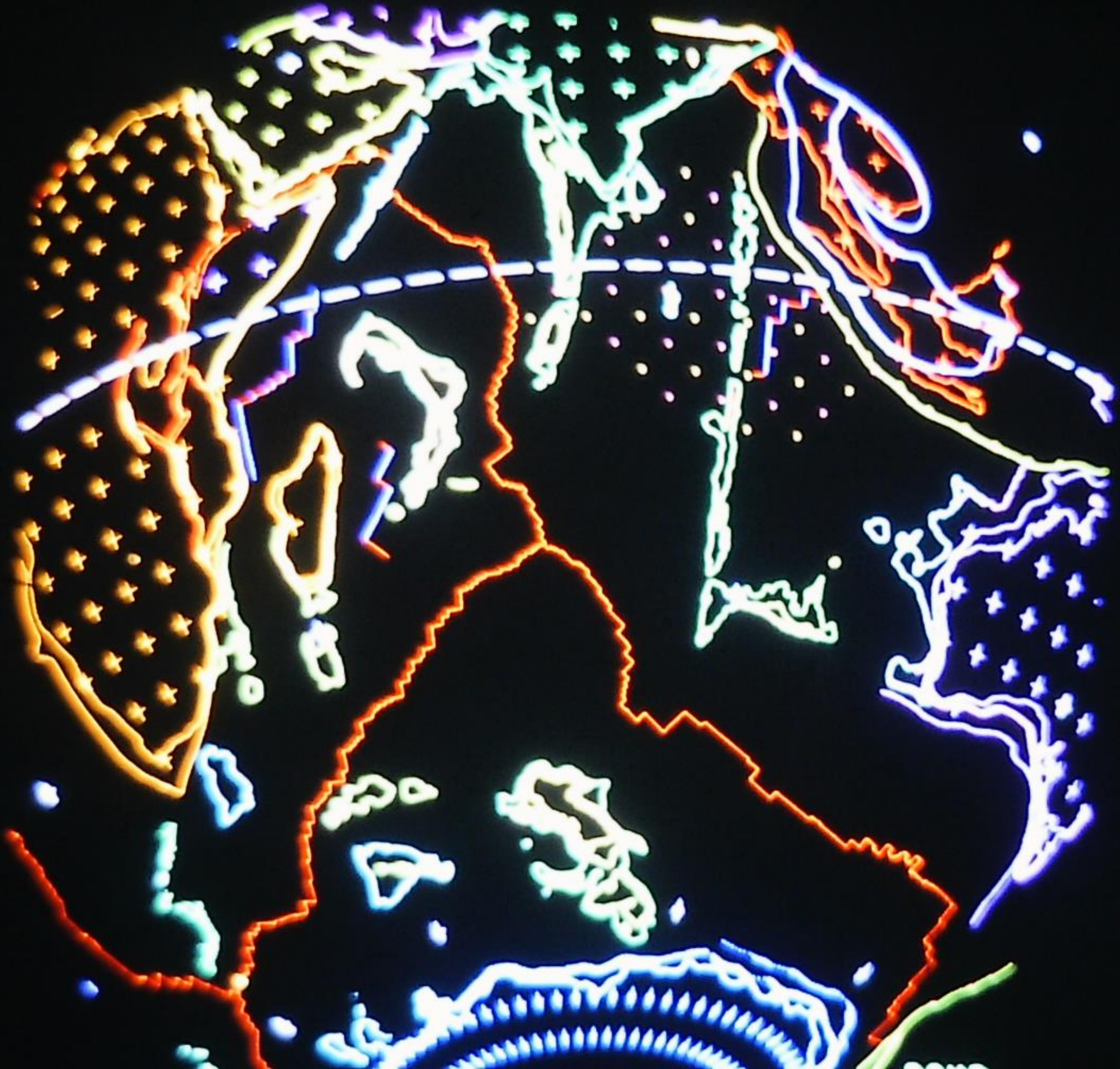
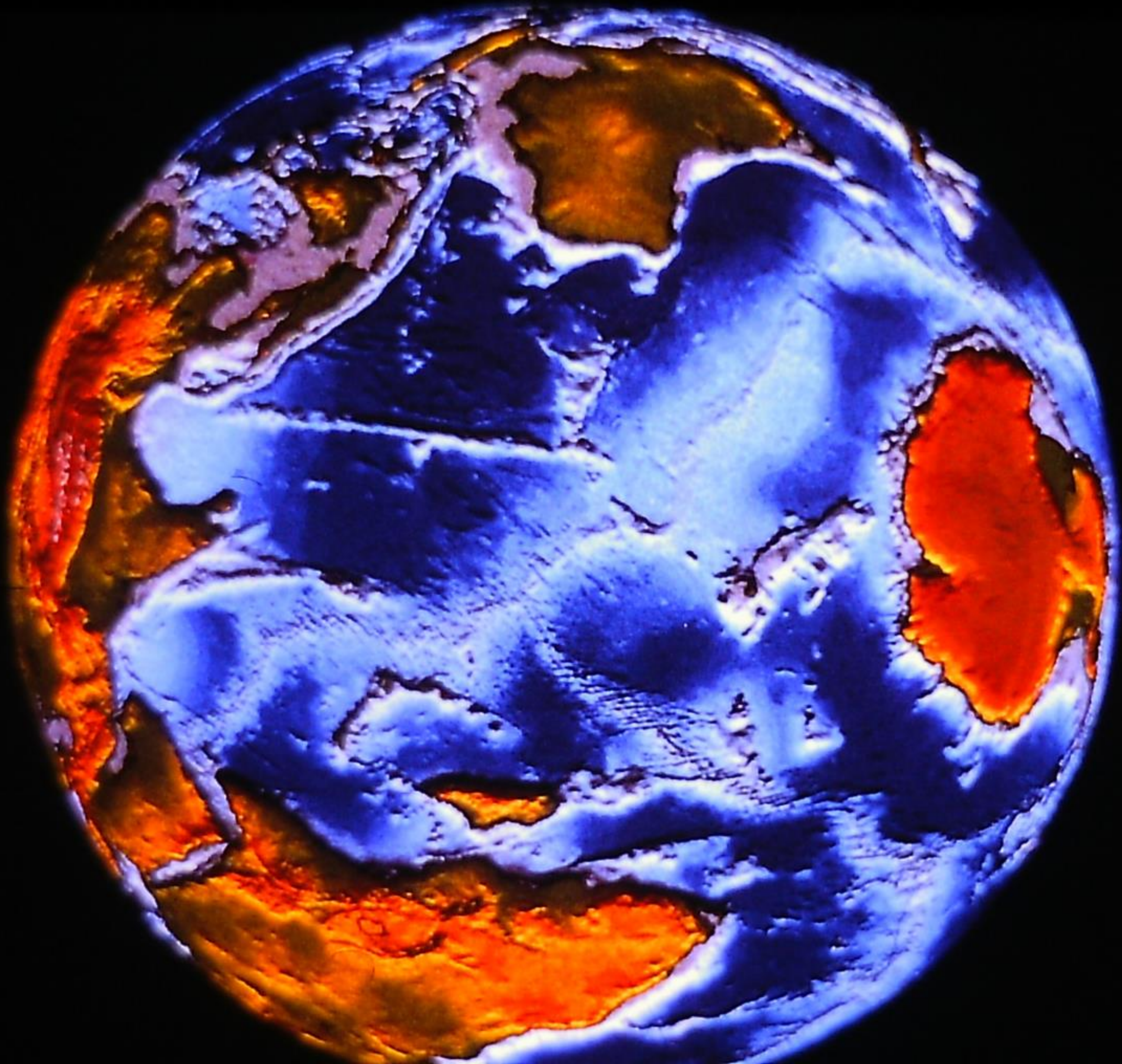
EVOLUTION OF THE PLATE GEOMETRY







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