PALEOCEANOGRAPHIC MAPPING PROJECT
PROGRESS REPORT NO. 34-1287

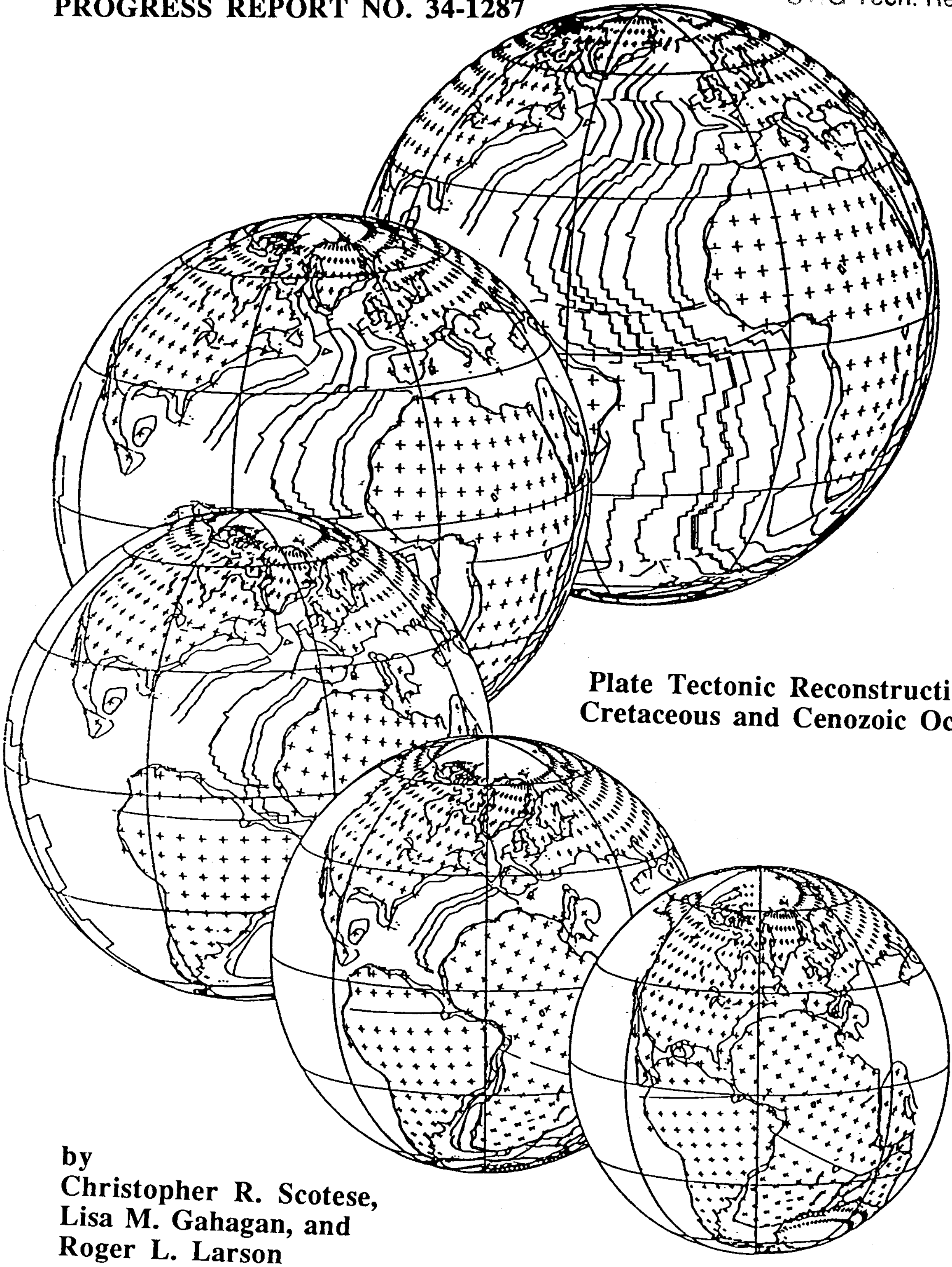

Plate Tectonic Reconstructions of the Cretaceous and Cenozoic Ocean Basins

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Abstract

In this paper we present nine reconstructions for the Mesozoic and Cenozoic, based on the sea-floor spreading isochrons published by Larson et al. (1985). The purpose of this study was: 1) to determine if the isochrons drawn by Larson et al. (1985) could be refitted to produce a self-consistent set of plate tectonic reconstructions, 2) to use the areas of apparent mismatch between magnetic isochrons as a focus for further investigations, and 3) to test the capabilities and accuracy of interactive computer graphic methods of plate tectonic reconstruction. In general, Tertiary and Late Cretaceous isochrons could be refitted reasonably well; however, closure errors were apparent in the vicinity of the Bouvet and Macquarie triple junctions. It was not possible to produce Early Cretaceous reconstructions that were consistent with the isochrons drawn by Larson et al. (1985). In this paper we also propose that the Late Cretaceous and early Tertiary plate reorganizations observed in the Indian Ocean were the result of the progressive subduction of an intra-Tethyan rift system.

Introduction

In 1985 a map illustrating the age of the ocean basins and continents was published by R.L. Larson, W.C. Pitman, S. Cande, W.F. Haxby, X. Golovchenko, and J. LaBreque (Figure 1). On this map, the oceans were divided into colored regions bounded by magnetic isochrons representing the following geologic time intervals: Pleistocene (chron 2, 1.9 Ma), Pliocene (chron 3a, 5.9 Ma), Miocene (chron 6b, 23 Ma), Oligocene (chron 15, 37.7 Ma), Eocene (chron 25, 59.2 Ma), Paleocene (chron 29 , 66.2 Ma), Late Cretaceous (chron 34, 84.0 Ma), mid-Cretaceous(chron M0, 118.7 Ma), and Early Cretaceous (chron M17, 143.8 Ma). The isochrons were drawn using published and unpublished magnetic anomalies and bathymetric information, and were modified to take into account new data from Seasat altimetry (Haxby, 1985). This map supercedes the maps of the age of the ocean floor published by Pitman et al. (1974) and Sclater et al. (1981).

In this study, we have used interactive computer graphics to produce plate tectonic reconstructions for each of the seafloor spreading isochrons described by Larson et al. (1985). The goals of this investigation were: 1) to determine if the isochrons mapped by Larson et al. could be refitted to produce a self-consistent set of plate tectonic reconstructions, 2) to use the areas of apparent mismatch between magnetic isochrons as a focus for further study, and 3) to test the capabilities and accuracy of interactive computer graphic methods of plate tectonic reconstruction. In the following sections we: outline the methods used to produce the reconstructions, discuss how well the isochrons can be refitted, review the major plate tectonic events illustrated in Figures 3-11, and consider the predictions made for relative plate motions across complex plate circuits.

Methods

Digitization of Map Data

The first step in our procedure was to encode map data into digital form. This was done using a 4 ' by 6' digitizing tablet and a computer program that converted X and Y map locations into latitude and longitude coordinates. The digitizing program automatically aligned the coordinate system of the digitizing tablet with the coordinate system of the map, corrected for the ellipticity of the Earth, and inverted the (X,Y) Cartesian coordinates obtained from digitizing tablet to spherical coordinates (latitude and longitude) using equations (1) and (2) for a Mercator projection where l and q respresent longitude and latitude, respectively, and c is a constant that depends on the scale of the map.

(1) $l = x/c$

(2) $q = 2 (\tan^{-1} (e\ y/c) - p/2$

At the beginning of each digitizing session, the intersections of known lines of latitude and longitude were digitized in order to verify that the map was properly aligned and that there were no other errors due to improper map projection or distortion. We required that the calculated latitude and longitude of known grid intersections were within .05 degrees of their true value. If the discrepancies were greater than .05 degrees, then the map was realigned.

Though the main function of the digitizing program was to convert X and Y map locations into coordinates of latitude and longitude, the program also recorded important information that was used to build a geographical database. This database consisted of bibliographic information, as well as a description of: the age of the feature, the plate with which it was travelling, and a simple coded description of the feature that was being digitized (for example, BA = bathymetric contour, RI = spreading ridge, CS = coastline, etc.). This information was later used by data management programs that searched and sorted the data, and by the interactive computer graphics and map-making programs that rotated and plotted the data as a function of plate identification and age.

Using Interactive Computer Graphics to Refit the Isochrons

After the map data had been digitized, it was displayed in color and manipulated using the Evans and Sutherland PS300 interactive computer graphics system. The Evans and Sutherland PS300 is a vector driven display device that can plot 20,000 3-D vector endpoints at a refresh rate of 30 updates a second. It has an effective screen resolution of 2,000 by 2,000 pixels. A small data tablet and the set of dials attached to the display permit real-time manipulation of three-dimensional data.

In a typical session, the user would sign-on and run the program MEGADRIFTER . A command menu would appear, and the user would then choose the menu option to open a geographic data file. The program then transferred a digitized data file from storage on disk or tape to the PS300. As the data were downloaded, the geographic outlines would be displayed on a globe, color-coded either by time or by plate identification. In this study, the isochrons of Larson et al. (1985) were color-coded by age.

After the geographic data had been transferred to the PS300, the user could begin to refit magnetic isochrons. The first step in this procedure was to activate one of the plates. To do this, the user would move the cursor attached to the data tablet along the surface of the tablet. A small "X" would appear on the PS300 display that corresponded to the position of the cursor on the tablet. The user would then position the "X" next to any of the line segments in the vector display. By gently depressing and releasing the cursor, the user could select a specific picture. Information about this picture was then sent to the program, which in turn activated the dials and special keyboard function buttons.

Once a picture, in this case a plate, was selected, the user could rotate all the geographical information associated with that plate about an arbitrary pole of rotation, the euler pole (LePichon et al., 1973). The location of the euler pole and angle of rotation about the pole could be entered directly through the keyboard or could be specified interactively through "dials" attached to the PS300 display. Three dials were required, one each for the latitude, longitude, and angle of rotation. The location of the euler pole and the amount of rotation were displayed in LED's above each dial.

By rotating the dials and adjusting the euler pole, isochrons could be visually superimposed. In a matter of a few minutes, a visual "best fit" could be determined. (A graphical test of this "best fit" is discussed in the following section.) After the "best fit" was achieved, the latitude, longitude and angle of the euler pole could be transferred to a permanent data file and the next set of isochrons could be refitted.

Graphical Test of the "Best Fit"

The computer graphic approach outlined above represents a novel way of making plate reconstructions. However, it is reasonable to ask, "How good are the best fits produced by this technique?" Though the "best fits" are arrived at subjectively, the results can be compared with independent and quantitative estimates of the best fitting rotations. The results of these comparisons are illustrated in Figure 2.

In order to test the accuracy of the interactive graphics approach, three isochrons in the South Atlantic were digitized and then refitted using both the interactive computer graphics approach and the method first described by McKenzie and Sclater (1971), subsequently modified by Pilger (1978) and Patriat (1983). Figure 2a is a contour plot that represents a surface whose "peak" is the location of an euler pole (54.8 N -31.80 W) that best fits Chron 25 on the African plate with its counterpart on the South American plate. The "best fit" pole determined independently by the interactive graphics technique is marked by the "+" that lies adjacent to the peak.

Similar contour plots of the "best fit" surface were made for Chron 15 and Chron 6 in the South Atlantic (Figure 2b and 2c). In both cases the euler pole determined by interactive computer graphics falls close to the calculated "best fit" pole. This graphical test, we feel, indicates that the poles determined by the interactive graphics technique are accurate estimates of the "best fit" pole, and that we are justified in using this technique to produce plate reconstructions. We, however, would agree with those who might argue that a combination of these techniques is the best approach, and are planning to modify the computer graphics software so that estimates of the goodness of fit are calculated interactively.

Mesozoic and Cenozoic Plate Tectonic Reconstructions

Figures 3 through 11 illustrate the opening of the modern ocean basins during the Cretaceous and Tertiary; a map has been produced for each of the magnetic isochrons illustrated on the Larson et al. (1985) map of The Bedrock Geology of the World. The age of the ocean floor is indicated by the stiple patterns of varying density and the mismatch of isochrons along the ridges is indicated by black (overlaps) and white (gaps) areas. The blank regions on the map represent areas of oceanic crust that have been removed by subduction.

The continental outlines and the location of sutures illustrated in Figure 1 are taken from Scotese et al. (1979) and Ziegler et al. (1983). The entire plate reconstruction has been reoriented with respect to the spin axis using the global apparent polar apparent wander path of Ziegler et al. (1983). The crosses that have been plotted on the continents represent a present-day, 5 degree graticule.

Late Tertiary : Chrons 2, 3a and 6b (Figures 3, 4 , and 5)

There is generally a good fit of the magnetic isochrons that were used to produce the reconstructions for the Late Tertiary (Chrons 2, 3a, and 6b). The only areas of notable misfit occur along the northwestern extension of the Central Indian Ridge in the Arabian Sea, between the Nazca and Pacific plates, and in the vicinity of the triple junction between Australia, Antarctica and the Pacific plates, south of Macquarie Ridge.

The major tectonic events during the Late Tertiary (Figures 3, 4, and 5) include the continued northward motion of India and Australia; the opening of the Red Sea (Cochran, 1983; LaBrecque and Zitellini, 1985), the Gulf of California (Larson et al., 1968; Atwater, 1970), and the Sea of Japan (Otsuki and Ehiro, 1979); the convergence and sinistral strike-slip movement along the Alpine Fault in New Zealand, and the breakup of the Farallon plate to form the Cocos and Nazca plates (Menard, 1978; Wortel and Cloetingh, 1981). The evolution of the Caribbean region is based on recent syntheses by Pindell and Barrett (1987) and Ross and Scotese (this volume).

In Figures 3 - 5, it is interesting to note the apparent widening gap between the subduction zone and the oceanic crust south of Indonesia and along the entire margin of the Pacific. The reconstruction of Southeast Asia shown in Figure 5 is a preliminary attempt to palinspastically restore the severe and complex deformation that resulted from the collision of India with Asia in the Early Tertiary . No attempt has been made to reconstruct, in detail, the tectonic evolution of the Scotia Sea or the marginal basins of the western Pacific.

Early Tertiary : Chrons 15 and 25 (Figures 6 and 7).

In Figure 6 (Chron 15, 37.7 Ma) there are wide gaps between the isochrons east of the Bouvet triple junction in South Atlantic and between the isochrons in the vicinity of southeastern Australia, south of the Tasman Rise. These problem areas persist in the Chron 25 reconstruction. In addition, in the Chron 25 reconstruction a wide gap occurs between the North and South Islands of New Zealand. This gap does not appear in older or younger reconstructions and is probably the result of errors within the Pacific/ Antarctic/ Australia/ New Zealand plate circuit. Also problematic is the gap between between the Indian and Antarctic plates just to the west of Broken Ridge. The gap that appears on the map between India and Africa represents the location of the Seychelles Islands and Mascarene Bank.

The major tectonic events during the Early Tertiary (Figures 6 and 7) include the collision of India with Asia (A22, 50 Ma; Patriat and Achache, 1984), the first phase of rifting in the South China Sea (Ru and Pigott, 1986), the termination of strike-slip motion along the Ninetyeast Ridge and the subsequent rapid separation of Australia from Antarctica (A19, 44.1 Ma; Cande and Mutter, 1982; Stock and Molnar, 1987), the cessation of seafloor spreading in the Labrador Sea (A20, 46.2 Ma; Srivastava and Tapscott, 1986) and Tasman Sea (A24, 56.1 Ma; Weissel and Hayes, 1977), and the opening of the eastern North Atlantic (A24, 56.1 Ma; Srivastava and Tapscott, 1986). It was also during the Early Tertiary (early Eocene) that extension and seafloor spreading began in the Cayman Trough, resulting in the eastward translation of the Caribbean plate relative to North and South America (Ross and Scotese, this volume). During the Early Tertiary the Apulian "prong" of Africa collided with Europe producing the Alps (Trumpy, 1982), and the western Cordillera of North America was uplifted during the Laramide orogeny (Coney, 1973).

Late Cretaceous : Chrons 29 and 34 (Figures 8 and 9).

Figures 8 and 9 illustrate the configuration of the continents and the ocean basins during the Late Cretaceous. Though the isochrons in the Central Atlantic superimpose reasonably well, there is a poor fit of the isochrons in the South Atlantic (Figure 9), especially in the vicinity of the Bouvet triple junction. In the Indian Ocean, there is a fair fit of the isochrons in the reconstruction of Chron 29 (Figure 8), however, large gaps are apparent in the Chron 34 reconstruction in the vicinity of the Bouvet triple junction and along the Southwest Indian Ridge near the Prince Edward Fracture Zone (Figure 9). There is also an unexplained gap between India and the Africa plate; and the Indian plate overlaps both Madagascar and Antarctica in the area of the Central Indian Ocean triple junction.

In the North Atlantic region during the Late Cretaceous, Iberia ceased to rotate with respect to Europe (A32, 73.5; Williams, 1975) and the Labrador Sea began to open (Quiet Zone, 95 Ma; Srivastava and Tapscott, 1986). During this same time interval, the Central and South Atlantic continued to widen, and the spreading center in the Agulhas Basin jumped westward (A29, 66.2 Ma; LaBrecque and Hayes, 1979), aligning itself with the overall N-S trend of the spreading axis in the South Atlantic (Figure 9). In the Indian Ocean, along the Southwest Indian Ridge, the spreading direction changed from NE directed spreading (Figure 8) to N-NW directed spreading (Figure 9) (Royer et al., this volume). Further to the northeast, India rapidly rifted away from Madagascar opening the Mascarene Basin (Figure 8), and in latest Cretaceous-earliest Tertiary, the spreading center in the Mascarene basin jumped northward to a location between India and the Seychelles (A28, 65.1 Ma; Schlich, 1982). As a result of this ridge jump, the Seychelles were transferred to the African plate and the proximity of the spreading axis to the margin of India may have triggered the eruption of the Deccan plateau basalts.

In the eastern Indian Ocean and southwest Pacific, rifting took place between Australia and Antarctica (Quiet Zone, 95 Ma; Cande and Mutter, 1982), New Zealand and Australia (A33, 80.2 Ma; Weissel and Hayes, 1977), and New Zealand and western Antarctica (Quiet Zone, 95 Ma; Kamp, 1986; Stock and Molnar, 1987; Norton et al., this volume). The initial spreading rate between Australia and Antarctica was slow (4.5 mm/yr) and a leaky, trans-tensional plate boundary connected the Australian-Antarctic rift with the Ninetyeast Ridge, which at that time was a major strike-slip boundary between the Indian and Australian plates. The Kerguelen and Broken Ridge plateaus were produced as a result of excess volcanism along this "leaky" plate boundary (Mutter and Cande, 1983; Ramsay et al., 1986; Coffin et al., 1986).

Early Cretaceous: Chrons M0 and M17 (Figures 10 and 11)

Although the Early Cretaceous isochrons in the Atlantic superimpose fairly well, the fit of the isochrons in the Indian Ocean is not satisfactory. As illustrated in Figure 10 there are large, unreconcilable overlaps between the isochrons on the Indian and Antarctica plates, and equally large gaps between the isochrons on the Antarctic and African plates. The problems are less severe for the Chron M17 reconstruction, however, a large overlap is evident between the isochrons in the Somali Basin.

The breakup of Pangea began in the Middle Jurassic and continued into the Early Cretaceous. The breakup of North America and Africa was preceded by extension and rift-related volcanic activity that extended back into the earliest Jurassic (Seidemann et al., 1984); the oldest identifiable magnetic anomaly in the Central Atlantic is M25 (157 Ma; Klitgord and Schouten, 1986), but separation probably occurred somewhat earlier (approx. 180 Ma) in the Jurassic magnetic Quiet Zone. Similarly, the breakup of eastern and western Gondwana was signalled by the extrusion of the extensive Karoo (Forster, 1975) and Ferrar (Kyle et al., 1981) basalts during the early Jurassic; however, the oldest oceanic crust in the Somali and Mozambique basins is Middle Jurassic in age (M25, 157 Ma; Segoufin and Patriat, 1981).

Seafloor spreading in the South Atlantic and between India and Antarctica appears to have been delayed until the Early Cretaceous. The oldest magnetic anomaly in the South Atlantic is M11 (133.5 Ma; Rabinowitz and LaBrecque, 1979) suggesting that the basin began to open in the Valanginian (130 Ma). The Early Cretaceous opening of the South Atlantic is confirmed by the presence of anomaly M12 (135.6 Ma; Goodlad et al., 1982) in the Natal Valley, suggesting that the Falkland plateau rifted away from southeast Mozambique during the Valanginian.

The timing of the separation of India from Antarctica/Australia is not as well constrained. Anomaly M11 in the Perth and Cuvier basin indicate that rifting between Australia and Greater India began in the Valanginian (133.5 Ma; Markl, 1978; Larson et al., 1979; Johnson et al., 1980; Veevers et al., 1985). Though no Early Cretaceous magnetic anomalies have been mapped between India and Antarctica, it is likely that India also separated from Antarctica at this time.

Discussion

Closure of Triple Junctions and across Complex Plate Circuits

As the reconstructions in Figures 3 through 11 illustrate, the isochrons of the Larson et al. (1985) map of The Bedrock Geology of the World can, in most areas, be used to produce accurate and informative plate tectonic reconstructions. Isochrons in the North and Central Atlantic, and along the Southwest Indian Ridge can be reconstructed with few gaps or overlaps. In the South Atlantic and Central Indian Ocean, however, the match between isochrons is not as good, especially for the older reconstructions.

The accuracy of the maps can also be evaluated by observing the closure of plates around triple junctions, and by noting the predicted relative motion of plates across complex plate circuits (for example, the motion of the Pacific plate relative to North America). In Figures 3 - 5 (Late Tertiary) closure is good along all triple junctions, with the exception of the triple junction south of the Macquarie Ridge (Australia-India-Pacific). In the Early Tertiary and Late Cretaceous reconstructions (Figures 6 and 7), there is fair closure across the Central Indian triple junction (Africa-Antarctica-India), and poor closure across the Kerguelen triple junction (Antarctica-Australia-India). Closure is also poor across the Bouvet triple junction (Africa-Antarctica-South America) and the Macquarie Ridge triple junction.

By refitting the isochrons, plate circuits can be constructed that predict the relative motion between pairs of plates for which there can be no direct measurement of relative motion. These predictions are especially useful in areas, such as the Circum-Pacific Basin and the Tethys, where subduction has removed vast areas of oceanic crust. Of particular interest, are the predicted relative motions between the Pacific and North America, and between Africa/India and Eurasia.

Pacific/North America Relative Motion

It is interesting to note that during the Late Cretaceous and Early Tertiary (Figures 6-9) the distance between the center of the Pacific plate and the western margin of North America does not change significantly. This suggests that new oceanic crust generated along the Farallon/Pacific spreading center (modern East Pacific Rise) nearly balanced the amount of oceanic crust subducted beneath western North America. This situation changed abruptly during the Late Tertiary, when North America overrode the East Pacific Rise (Figure 6). As recorded in the bend of the Emperor-Hawaiian hot spot track, the Pacific then began to move rapidly to the northwest, parallel to the western margin of North America (Figures 3-6).

Solution of Motion Across the Alpine Fault (New Zealand)

The motion between the northern and southern halves of New Zealand along the Alpine Fault was constrained by the plate circuit South New Zealand/Pacific/Marie Byrdland/E. Antarctica/Australia/N. Zealand. In our model, South New Zealand was considered to be part of the Pacific plate and no subduction was presumed to have taken place along the southern margin of the Campbell plateau or along the northern margin of Marie Byrdland since the Late Cretaceous (95 Ma). Also no attempt was made to palinspastically restore the severely deformed shapes of North and South New Zealand. As illustrated in Figures 6 - 11, North and South New Zealand remained in the same relative positions during the Cretaceous and Early Tertiary. Major movement on the Alpine Fault did not begin until the early Miocene (Figures 3-5).

The Closure of Tethys and Plate Reorganizations in the Indian Ocean

As illustrated in Figures 8 through 11, a wide Tethys Ocean separated India from southern Asia during the Early Cretaceous. During the Late Cretaceous, Tethys narrowed as India rifted away from Madagascar and moved rapidly northward. The collision of Greater India and Asia occurred during the Early Eocene, approximately 50 million years ago (Patriat and Achache, 1984). Immediately following the collision of India, spreading rates between Australia and Antarctica increased, and Australia rapidly separated from Antarctica (Figures 3 - 6).

Although this sequence of events is well-documented, the causes of these changes in plate motion are not well understood. In Figure 12, we have drawn hypothetical plate boundaries in the Tethys Ocean. We propose that the progressive subduction of these plate boundaries was directly responsible for the plate tectonic reorganizations observed to the south in the Indian Ocean.

Late Jurassic seafloor spreading in the Somali Basin documents the breakup of eastern and western Gondwana (Segoufin and Patriat, 1981). It is interesting to note that magnetic lineations in the Argo abyssal plain along the northwest coast of Australia indicate that an unidentified tectonic element rifted from Australia at the same time (Heirtzler et al., 1978; Larson, 1975; Veevers et al., 1985b). The relative motion predicted by the lineations in the Somali and Argo abyssal plain is very similar, and we suggest that these two spreading centers were once part of the same rift system, which we term the "Tethyan Rift" (Figure 12a). Eastern Gondwana (Greater India and Australia) was located south of the Tethyan Rift; to the north of the spreading center was the "Neo-Tethyan plate". During the Late Jurassic and Early Cretaceous, as new ocean floor was generated at the Tethyan Rift, the older portions of the Neo-Tethyan Plate were subducted beneath the southern margin of Eurasia (Sengor, 1985).

Seafloor spreading along the Tethyan Rift continued during the Early Cretaceous and the spreading center moved steadily northward (Figure 12b). Rifting between India and Australia during the Early Cretaceous, resulted in the formation of a new triple junction between the Indian, Australian, and Neo-Tethyan plates (Figure 12b).

During the mid-Cretaceous, the Tethyan Rift continued to move northward as the Neo-Tethyan plate was subducted beneath Eurasia. We propose that about 95 million years ago, a major plate reorganization took place as a result of the subduction of the western portion of the Tethyan Rift (Figure 12c). As a consequence of the elimination of the western portion of the Neo-Tethyan plate, the Indian plate began to be subducted beneath Eurasia. We suggest that it was the initial subduction of the Indian plate that caused the breakup of India and Madagascar and resulted in the increase in spreading rates along the Central and Southeast Indian ridges. This plate reorganization may also have been responsible for the drastic changes in spreading directions observed in the Wharton and Cuvier basins. In this region, during the Cretaceous Quiet Zone, spreading directions changed approximately 45 degrees, from N-NW (Wallaby and Perth Fracture Zones) to N-S (90° E Ridge and Investigator Fracture Zone). Our model would also predict that an important orogenic event took place along the southern margin of Eurasia during the Mid-Cretaceous as a result of the thermal pulse generated by the subduction of the western portion of the Tethyan rift.

As illustrated in Figure 12c, we indicate that though the western portion of the Tethyan Rift was subducted, the eastern portion of the Tethyan Rift continued to generate ocean floor between Australia and Southeast Asia. As illustrated in Figure 12a-e, the distance between northern Australia and Southeast Asia remained relatively constant from the Late Jurassic through to the Early Tertiary, suggesting that there was a balance between subduction and sea-floor spreading.

During the Late Cretaceous and Early Tertiary, India moved rapidly northward as the Indian plate continued to be directly subducted beneath the southern margin of Eurasia (Figure 12d-e). In the Early Eocene, Greater India collided with Eurasia (A22, 50 Ma;

Patriat and Achache, 1984). At about the time of the collision, and possibly as a direct result of it, spreading in the Wharton Basin stopped (A20, 46.2 Ma; Liu et al., 1983) and the Indian and Australian plates were fused to form the modern Indo-Australian plate. As in the case of the Indian plate during the Late Cretaceous, the Indo-Australian plate began to be subducted directly beneath Eurasia. We suggest that it was the subduction of the Indo-Australian plate that caused the ultimate breakup of Australia and Antarctica, resulting in the increase in spreading rate along the Australia/Antarctica plate boundary (Cande and Mutter, 1982)

Conclusion

How well do the Larson et al. (1985) isochrons work?

The isochrons drawn by Larson et al. (1985) can be used to produce reasonably accurate plate tectonic reconstructions (Figures 4 - 11). These reconstructions represent a comprehensive, yet preliminary, synthesis of our understanding of Mesozoic and Cenozoic plate motions. Because much of the data used to draw the isochrons was compiled between 1977 and 1983, it is inevitable that more recent work will supercede and refine the plate tectonic model presented here (Table 1). In this regard, these maps should be viewed as a 'first draft' that lays the groundwork for future efforts.

Although the Larson et al. (1985) sea-floor spreading isochrons work well for the Late Cretaceous and Tertiary, the match of Early Cretaceous isochrons in the Indian Ocean is unsatisfactory. The misfit between India, Africa, and Antarctica highlights an important problem that will require additional study. As pointed out in the text, other persistent problems include: poor closure across the Macquarie and Bouvet triple junctions, misfit along the Southwest Indian Ridge, and the mismatch of Late Cretaceous isochrons in the South Atlantic.

We also believe that this paper demonstrates that interactive computer graphics is a useful and effective tool for producing plate tectonic reconstructions. The three-dimensional capabilities of the computer graphics display device (Evans and Sutherland PS300), combined with the ability to rotate and manipulate plate outlines in real time, allow the user to take full advantage of the plate tectonic paradigm. Because the graphics computer so easily handles the three-dimensional aspects, the user is free to integrate and synthesize the data, using the most powerful image-processing device available - the human brain. As we illustrated in Figure 2, the best-fitting poles of rotation derived using interactive computer graphics are comparable to the solutions determined by direct computation.

What have we learned: Global Synchroneity and Slab Pull as the Major Driving Force of Plate Tectonics.

Finally, in any large-scale synthesis it is important to ask the question, "What new things have we learned?". The greatest strength of any historical science, like geology, is the perspective that time brings. Looking at today's world, we have only one example of the plate tectonic system; however, by reviewing the history of plate motion during the Mesozoic and Cenozoic, we may be able to discern patterns that are not apparent on a shorter timescale.

A brief review of the model presented in this paper reveals two major features of Mesozoic and Cenozoic plate evolution: 1) global synchroneity of major changes in plate motion and, 2) the importance of 'slab pull' as the major driving force in plate tectonics. A brief tabulation of the timing of changes in plate motion reveals that there have been five major events during the Mesozoic and Cenozoic. These events are: 1) the breakup of Pangea and Gondwana during the Middle Jurassic (Quiet Zone, 175 Ma), 2) the breakup of southern continents (Africa-S. America, Antarctica/Australi-India) during the Early Cretaceous (M11, 133.5 Ma), 3) the mid-Cretaceous plate reorganization (Quiet Zone, 95 Ma) , 4) the latest Cretaceous plate reorganization (A28; 65.1 Ma), and 5) the plate reorganization that followed the collision of India with Asia in the Early Eocene (A21; 50.3 Ma).

The synchroneity of these plate tectonic events has two important implications. The first implication is that the plate motions are connected. What happens in one ocean basin, or along one plate boundary, effects surrounding plates, as well as plates on the other side of the Earth. The nature of this connectivity, however, is not well understood. The second implication of synchroneity is that there is a distinct cause, or trigger, that sets off the chain reaction that we interpret as a major plate reorganization. We propose that plate reorganizations are triggered by the subduction of a major ridge system, or the elimination of a subduction zone as a result of continental collision. The plate reorganizations that took place in the Indian Ocean can easily be interpretted to follow this pattern.

As mentioned above, the second major lesson to be learned from the pattern of Mesozoic and Cenozoic plate motions is the importance of 'slab pull'. Numerous authors have proposed that slab pull, or the force due to the negative bouyancy of the old, cold lithosphere, is the major driving force of plate tectonics. However, because the dynamics of plate motion are not well known, there is no agreement regarding the importance of slab pull relative to the other proposed driving mechanisms.

A review of the historical evidence, we believe, indicates that slab pull and geometry of subduction zones is the first order cause of plate motions. As in the case of the reorganizations in the Indian Ocean, or the breakup of the Farallon plate to form the Nazca and Cocos plates, it is the events at the subduction zone that produce changes in plate motion and create new plate geometries. It appears that spreading centers, though an important component of the system, passively follow the orders eminating from the trenches.

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TABLE 1

Euler poles of rotation

Chron	Time (Ma)	Latitude	Longitude	Angle	Reference
		North America relative to Africa			
2	1.9	80.44	56.37	0.37	
3a	5.9	82.40	43.10	1.44	
6b	23.0	80.43	56.36	5.37	
15	37.7	77.61	7.21	10.63	
25	59.2	79.10	7.07	17.05	
29	66.2	80.59	-14.76	22.50	
34	84.0	78.35	-12.13	28.52	
M0	118.7	66.41	-19.61	54.12	
M17	143.8	67.07	-18.05	59.23	
		Greenland relative to North America			
13	35.9	0.00	0.00	0.00	
25	59.2	-16.26	28.48	2.37	
29	66.2	-41.70	35.94	5.14	
34	84.0	-39.63	30.94	7.91	
Closure	92.0	-50.07	26.29	7.74	Lawver and Scotese (1986)
		South America relative to Africa			
2	1.9	68.75	-41.47	0.62	
3a	5.9	66.57	-37.30	2.02	
6b	23.0	52.67	-31.64	7.71	
15	37.7	55.85	-32.83	14.32	
25	59.2	55.85	-32.83	21.62	
29	66.2	55.87	-32.83	25.13	
34	84.0	59.77	-35.40	33.13	
M0	118.7	48.82	-32.90	52.34	
Closure	138.0	44.50	-32.20	58.20	Lawver and Scotese (1986)
		Eurasia relative to North America			
2	1.9	-65.85	-47.56	0.43	
3a	5.9	-65.85	-47.56	1.44	
6b	23.0	-30.43	-38.30	4.25	
15	37.7	-73.30	-49.70	9.01	
25	59.2	-43.50	-34.60	12.39	
29	66.2	-65.43	-32.04	16.35	
34	84.0	-65.83	-22.85	19.33	
Closure	92.0	-69.34	-33.20	23.61	Lawver and Scotese (1986)

TABLE 1 (continued)

Chron	Time (Ma)	Latitude	Longitude	Angle	Reference
			Spain relative to Eurasia		
29	66.2	0.00	0.00	0.00	
34	84.0	-46.22	-174.65	5.05	
Closure	92.0	-50.08	-179.43	30.40	
			India relative to Africa		
2	1.9	-32.80	-154.09	1.22	
3a	5.9	-35.39	-149.70	3.35	
6b	23.0	-17.27	-133.98	12.23	
15	37.7	-15.25	-135.09	19.82	
25	59.2	-15.36	-144.40	34.27	
29	66,2	-12.48	-147.79	46.56	
34	84.0	-18.72	-154.61	54.26	
Closure	92.0	-21.28	-154.24	57.66	Lawver and Scotese (1986)
			Madagascar relative to Africa		
M0	118.7	0.00	0.00	0.00	
M17	143.8	82.21	-90.85	12.15	(interpolated)
			Australia relative to Antarctica		
	0.0	0.00	0.00	0.00	
15	37.7	-13.70	-151.21	21.69	
25	59.2	-10.70	-146.93	24.01	
29	66.2	-1.64	-144.23	26.43	
34	84.0	-8.93	-150.11	26.54	
Closure	95.0	-1.58	-140.98	31.29	Lawver and Scotese (1986)
			Antarctica relative to Africa		
2	1.9	18.55	-36.41	0.33	
3a	5.9	9.45	-41.72	0.82	
6b	23.0	9.46	-41.70	3.34	
15	37.7	8.73	-36.52	5.93	
25	59.2	-1.56	-37.65	8.94	
29	66.2	-2.82	-42.18	11.46	
34	84.0	-1.52	-40.03	17.23	
			Antartica relative to India		
34	84.0	7.88	14.80	64.34	
Closure	130.0	-4.44	16.74	92.77	Lawver and Scotese (1986)

TABLE 1 (continued)

Chron	Time (Ma)	Latitude	Longitude	Angle	Reference
North New Zealand relative to Australia					
	50.0	0.00	0.00	0.00	
25	59.2	5.26	-24.14	0.73	
29	66.2	9.67	-38.82	7.31	
Closure	95.0	24.19	-19.91	44.61	Lawver and Scotese (1986)
South New Zealand relative to Marie Byrdland					
2	1.9	68.71	-98.50	1.88	
3a	5.9	75.84	-60.93	6.46	
6b	23.0	73.35	-62.84	16.62	
15	37.7	74.97	-53.67	28.96	
25	59.2	71.40	-59.57	38.28	
29	66.2	69.78	-58.86	46.14	
34	84.0	65.10	-55.29	43.30	
Closure	95.0	65.14	-52.00	62.38	Lawver and Scotese (1986)
Pacific relative to Marie Byrdland					
2	1.9	68.71	-98.50	1.88	
3a	5.9	75.84	-60.93	6.46	
6b	23.0	73.35	-62.84	16.62	
15	37.7	74.97	-53.67	28.96	
25	59.2	71.40	-59.57	38.28	
29	66.2	69.78	-58.86	46.14	
34	84.0	65.10	-55.29	43.30	
Closure	95.0	65.14	-52.00	62.38	Lawver and Scotese (1986)
Nazca relative to Pacific					
2	1.9	-53.01	86.61	3.58	
3a	5.9	-63.15	91.01	9.03	
6b	23.0	-60.85	90.63	38.91	
15	37.7	-69.20	80.47	51.78	
25	59.2	-78.84	60.18	67.20	
Cocos relative to Pacific					
2	1.9	-38.72	72.61	3.96	Minster and Jordan (1978)
3a	5.9	-44.17	68.87	9.57	

Figure Captions

Figure 1. Isochron Map illustrating the age of the ocean basins modified after Larson et al. (1985). Fine light stipple = chrons 2, 3a, and 6; fine dark stipple = chrons 15 and 25; coarse light stipple = chrons 29 and 34; coarse dark stipple = chrons M0 and M17. Continental sutures after Scotese et al. (1979), Ziegler et al. (1983), and Ross and Scotese (this volume).

Figure 2. Contour plot that represents a surface whose "peak" is the location of best-fitting euler poles for the closure of South Atlantic isochrons for (a) chron 25, (b) chron 15, and (c) chron 6. The star represents the euler pole determined by using interactive graphics, the cross is the location of the best-fitting euler pole determined using the method of McKenzie and Sclater (1973), Pilger (1978), and Patriat (1983).

Figure 3. Plate Reconstruction for Chron 2 (Pleistocene, 1.9 Ma). For description of shading, see Figure 1.

Figure 4. Plate Reconstruction for Chron 3a (Pliocene, 5.9 Ma). For description of shading, see Figure 1.

Figure 5. Plate Reconstruction for Chron 6b (Miocene, 23 Ma). For description of shading, see Figure 1.

Figure 6. Plate Reconstruction for Chron 15 (Oligocene, 37.7 Ma). For description of shading, see Figure 1.

Figure 7. Plate Reconstruction for Chron 25 (Eocene, 59.2 Ma). For description of shading, see Figure 1.

Figure 8. Plate Reconstruction for Chron 39 (Paleocene, 66.2 Ma). For description of shading, see Figure 1.

Figure 9. Plate Reconstruction for Chron 34 (Late Cretaceous, 84 Ma). For description of shading, see Figure 1.

Figure 10. Plate Reconstruction for Chron M0 (mid-Cretaceous, 118.7 Ma). For description of shading, see Figure 1.

Figure 11. Plate Reconstruction for Chron M17 (Early Cretaceous, 143.8 Ma). For description of shading, see Figure 1.

Figure 12. Hypothetical plate boundaries in Tethys during the Mesozoic and Cenozoic. (a) Early Cretaceous (chron M17), (b) mid-Cretaceous (chron M0), (c) Cretaceous magnetic Quiet Zone (Approx. 95 Ma), (d) Late Cretaceous (chron 34), (e) Paleocene (chron 29), and (f) Oligocene (chron 15).

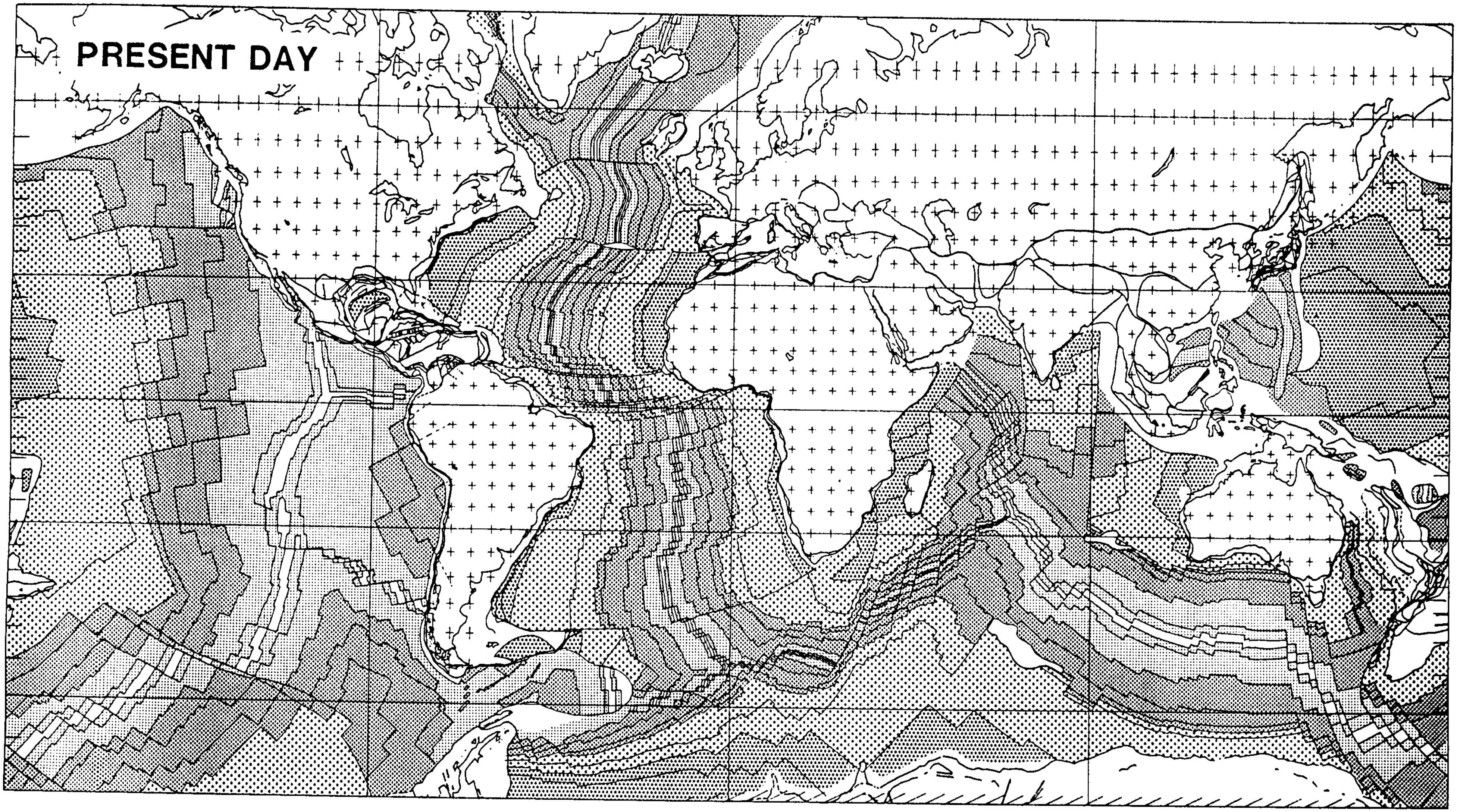


Figure 1.

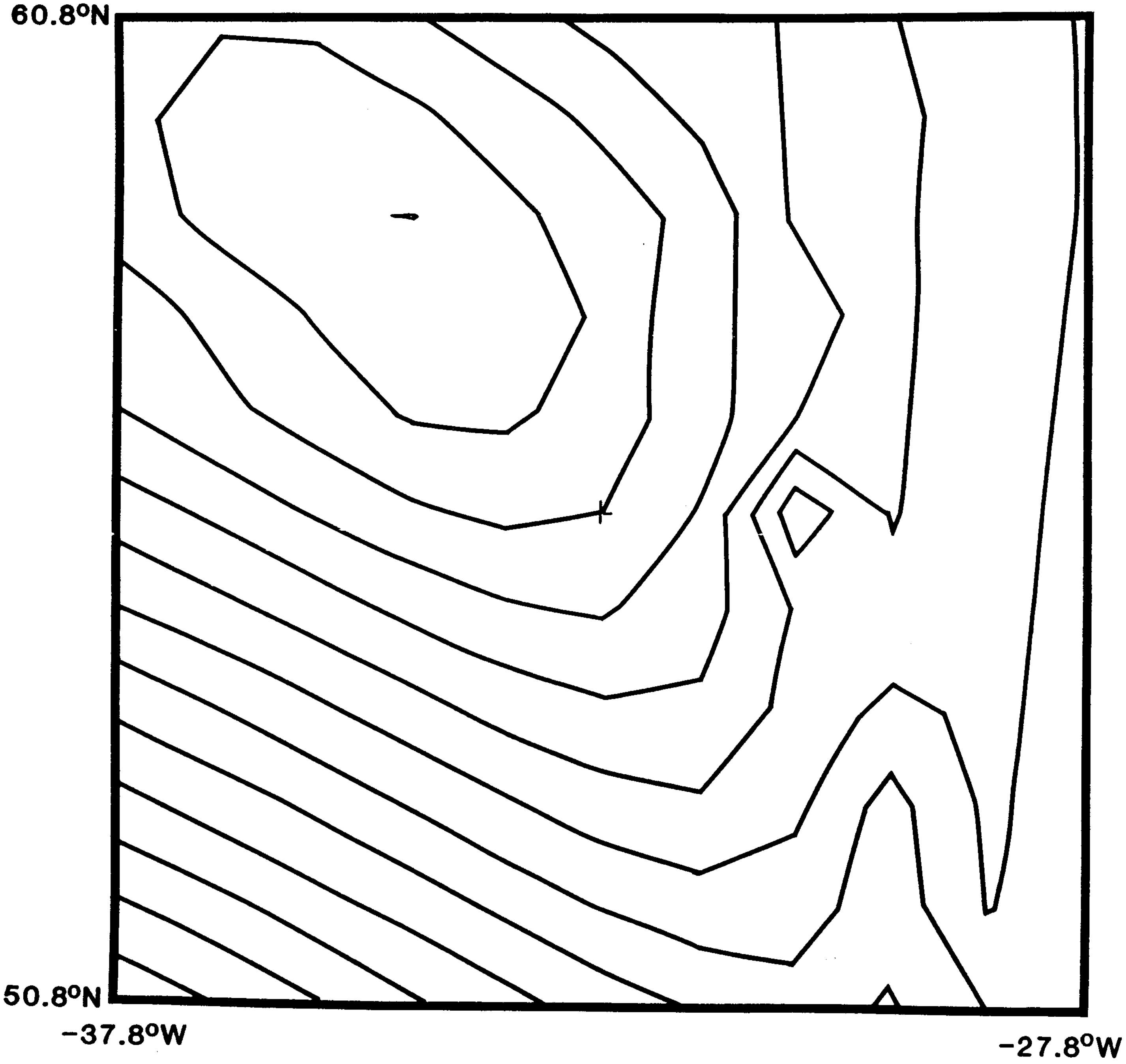


Figure 2a.

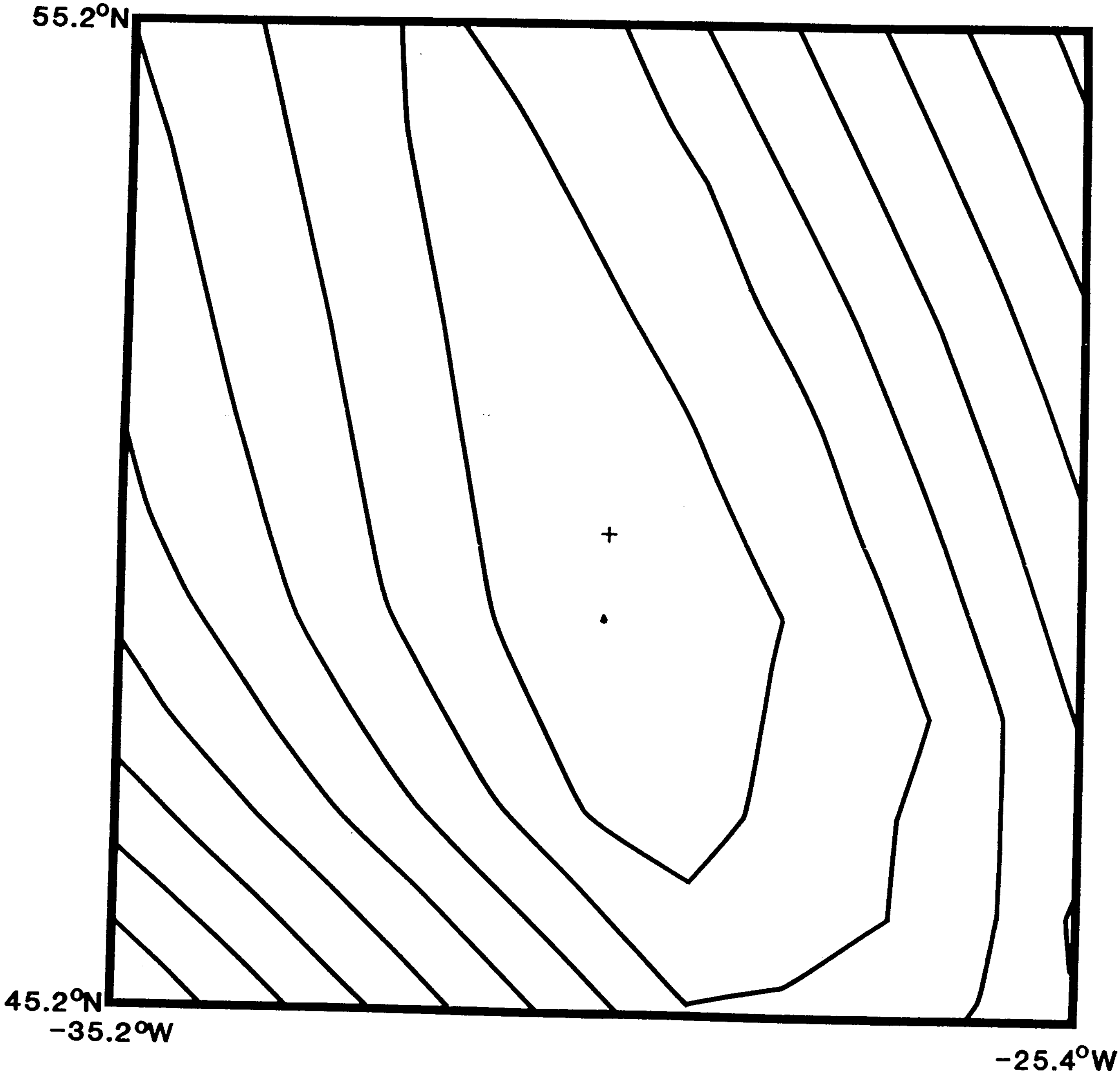


Figure 2b.

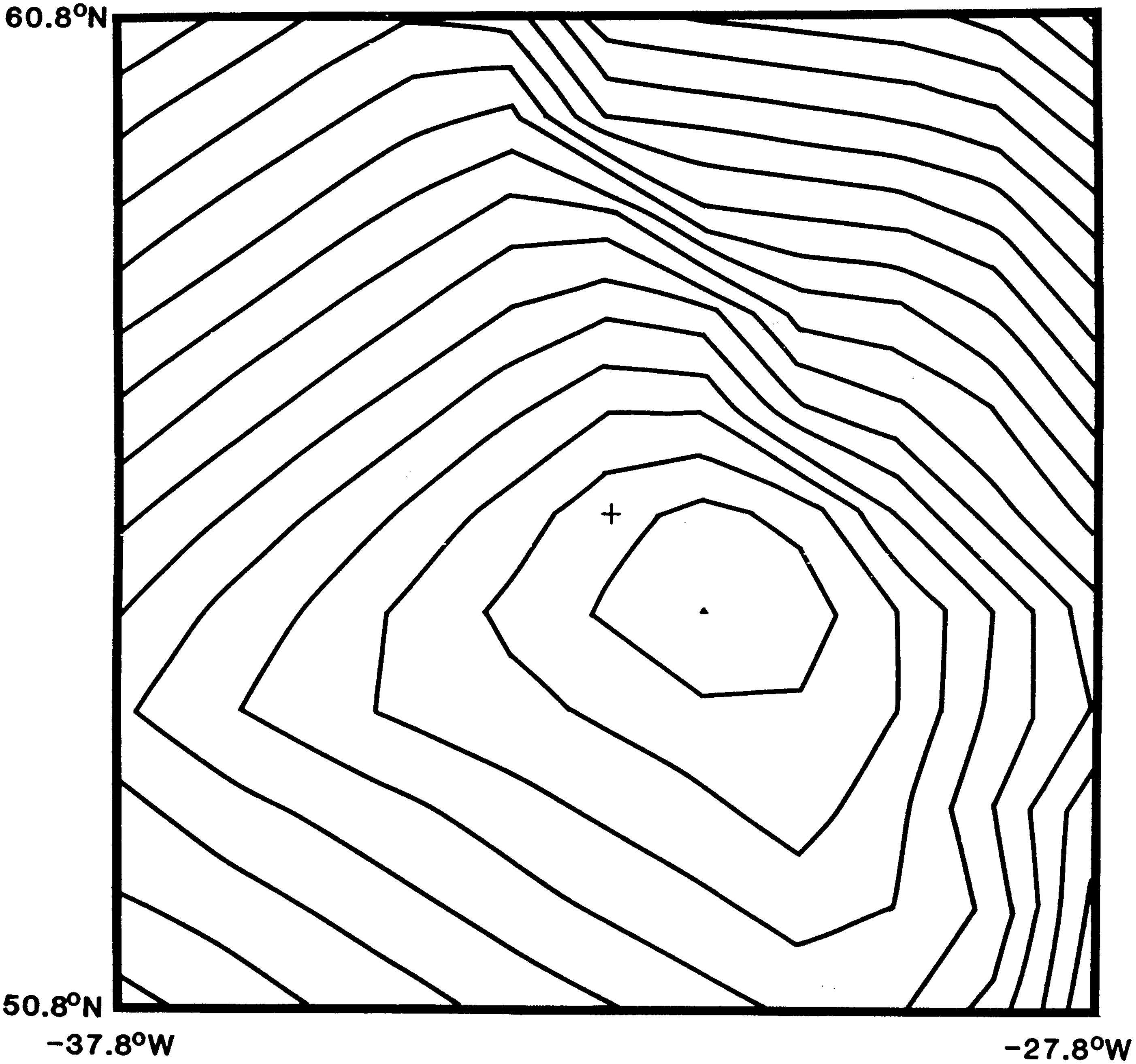
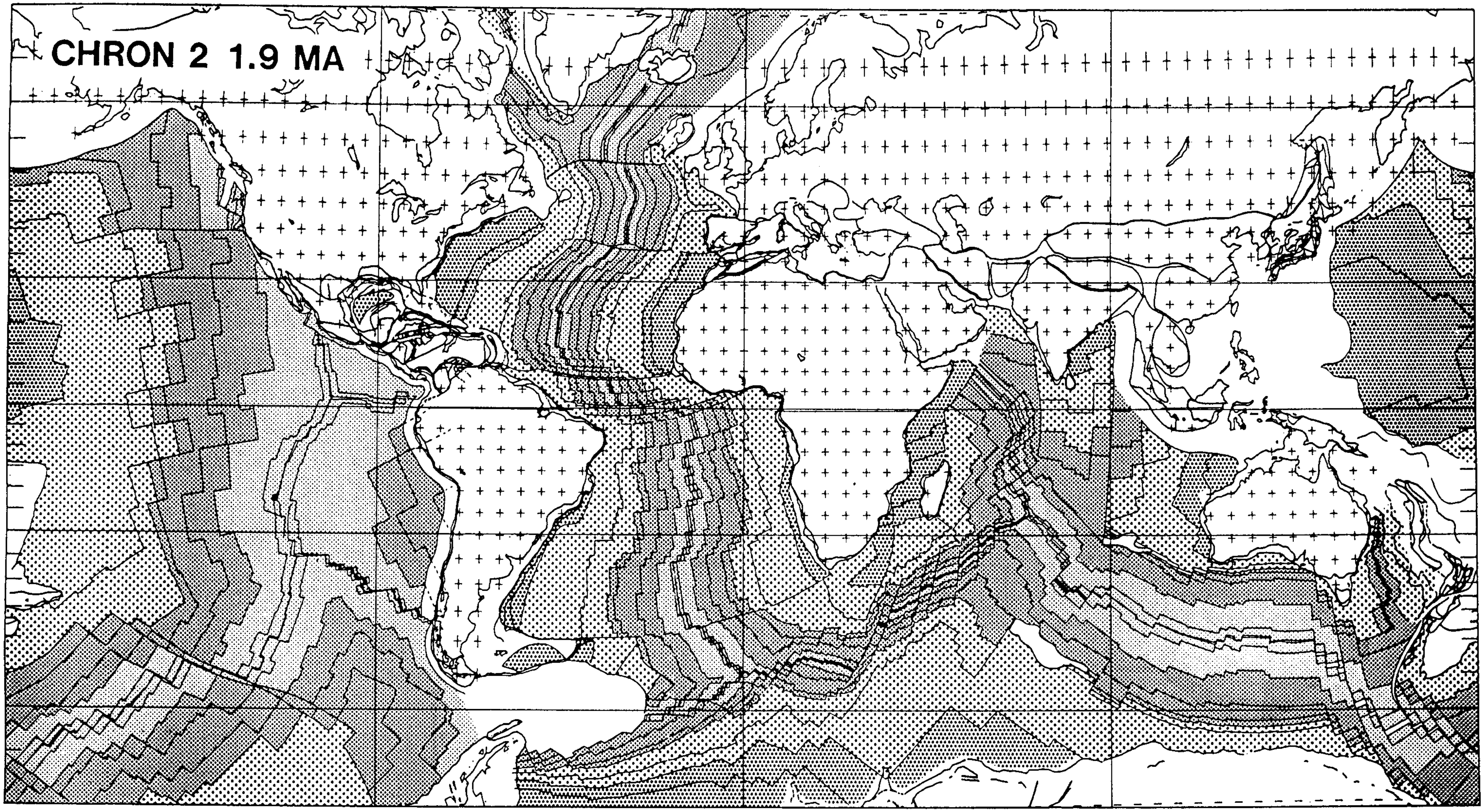


Figure 2c.



CHRON 2 1.9 MA

Figure 3.

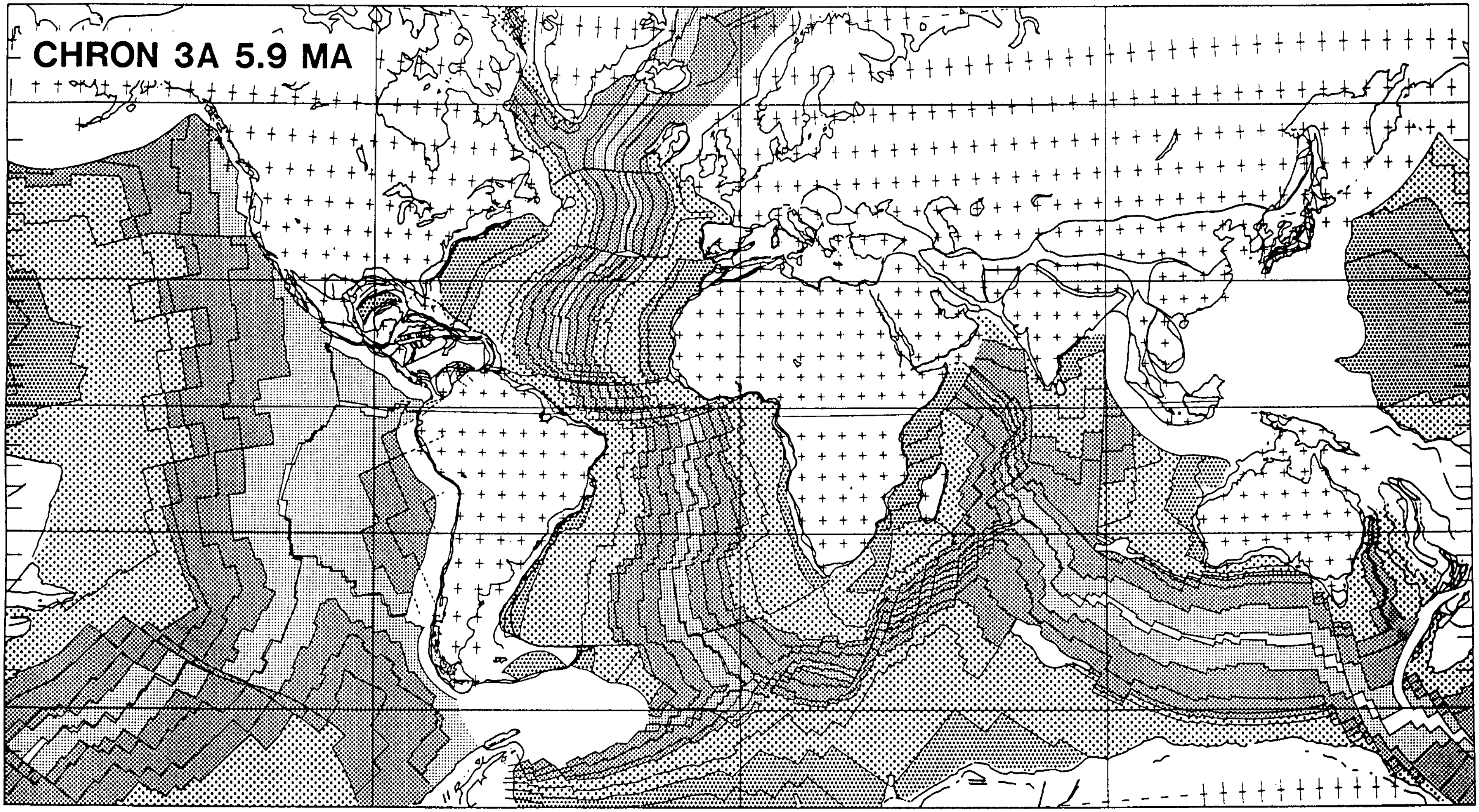


Figure 4.

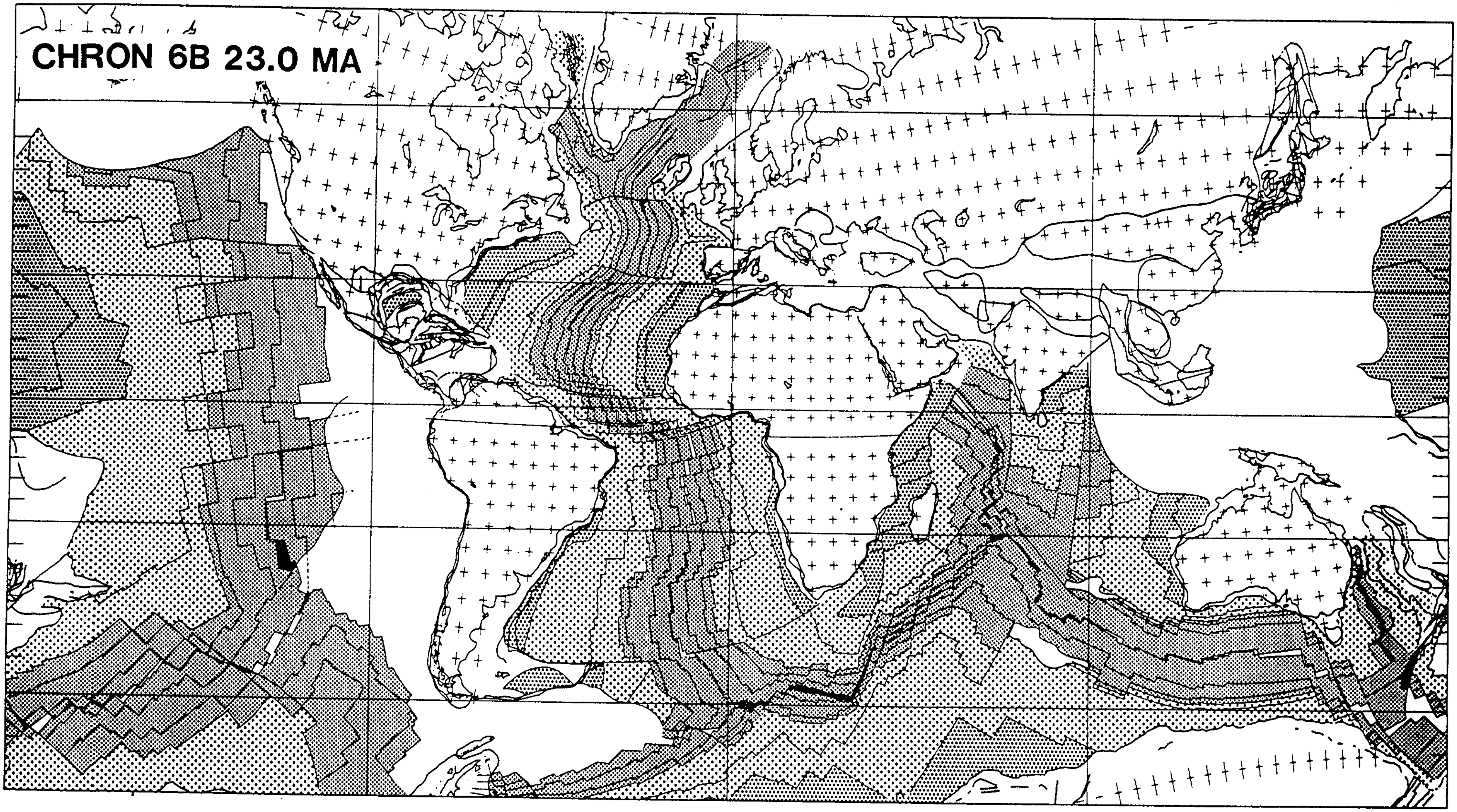


Figure 5.

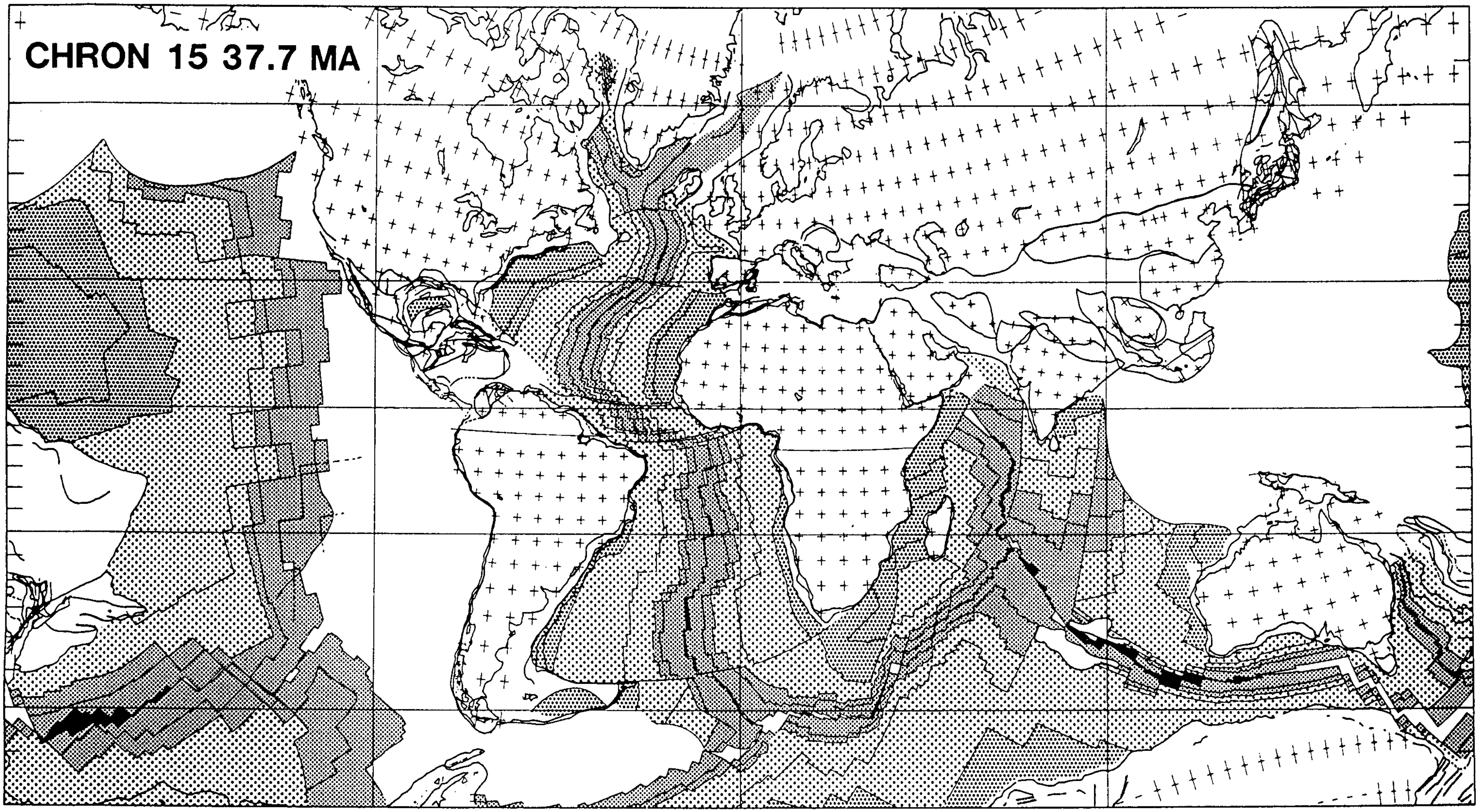


Figure 6.

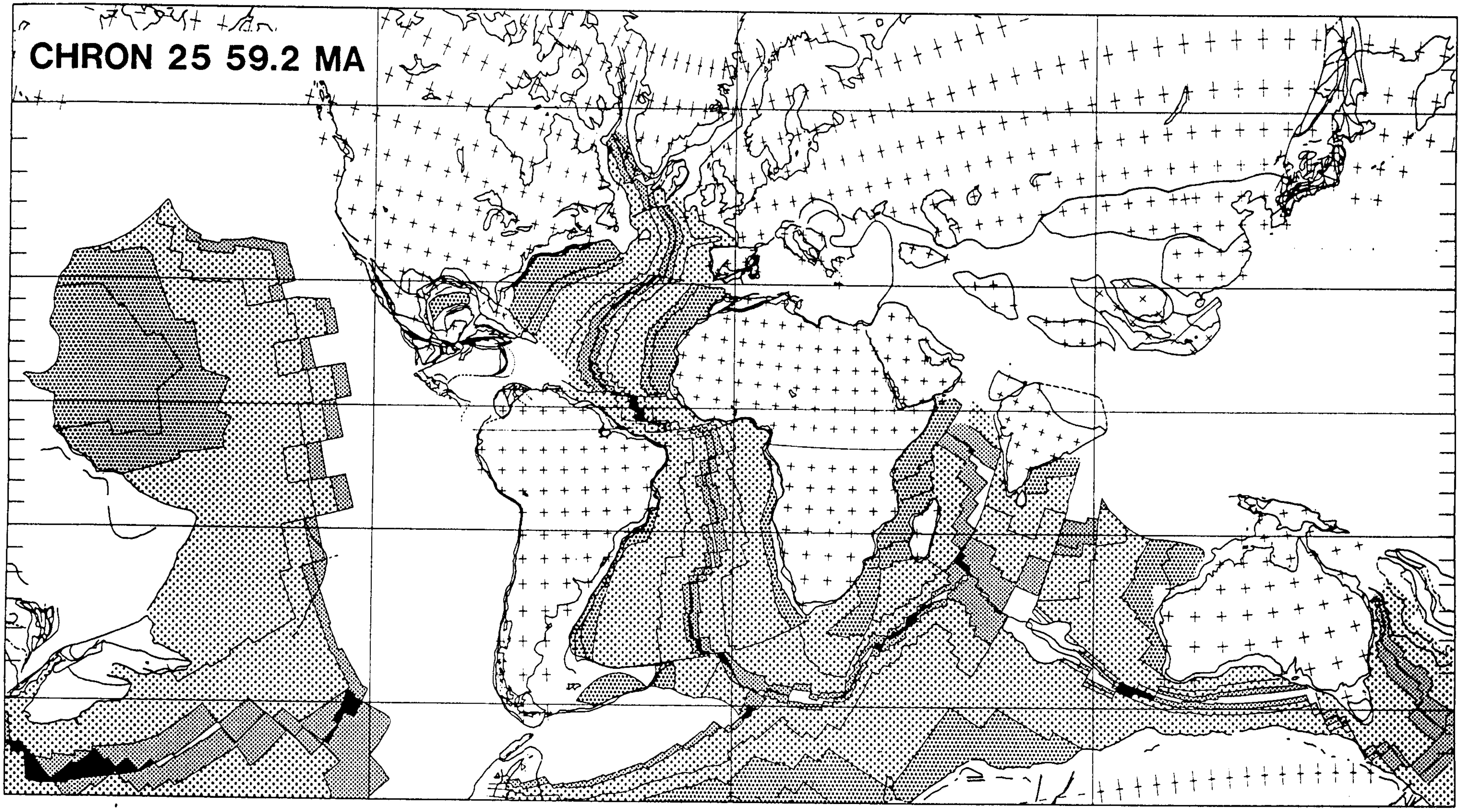


Figure 7.

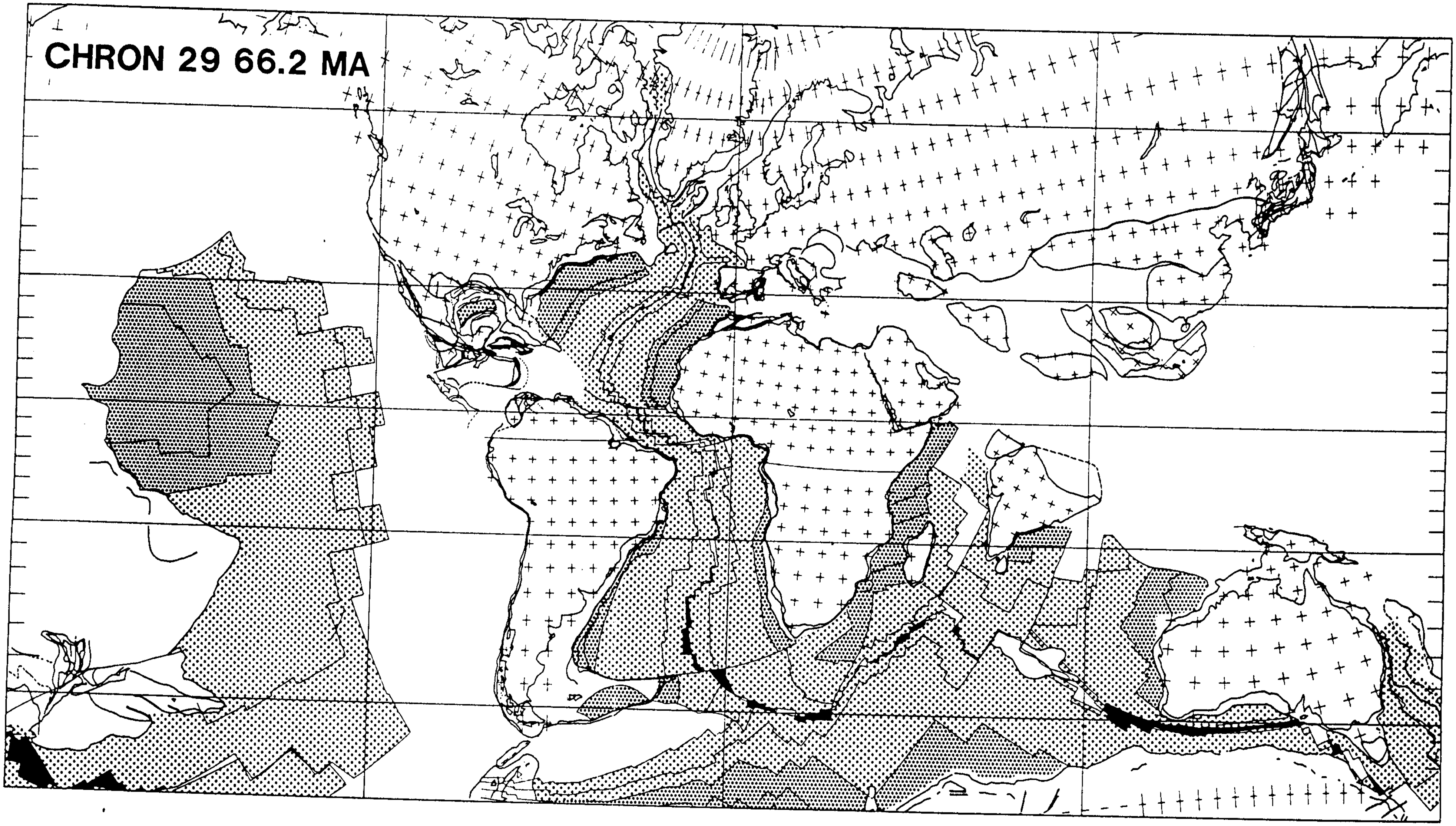


Figure 8.

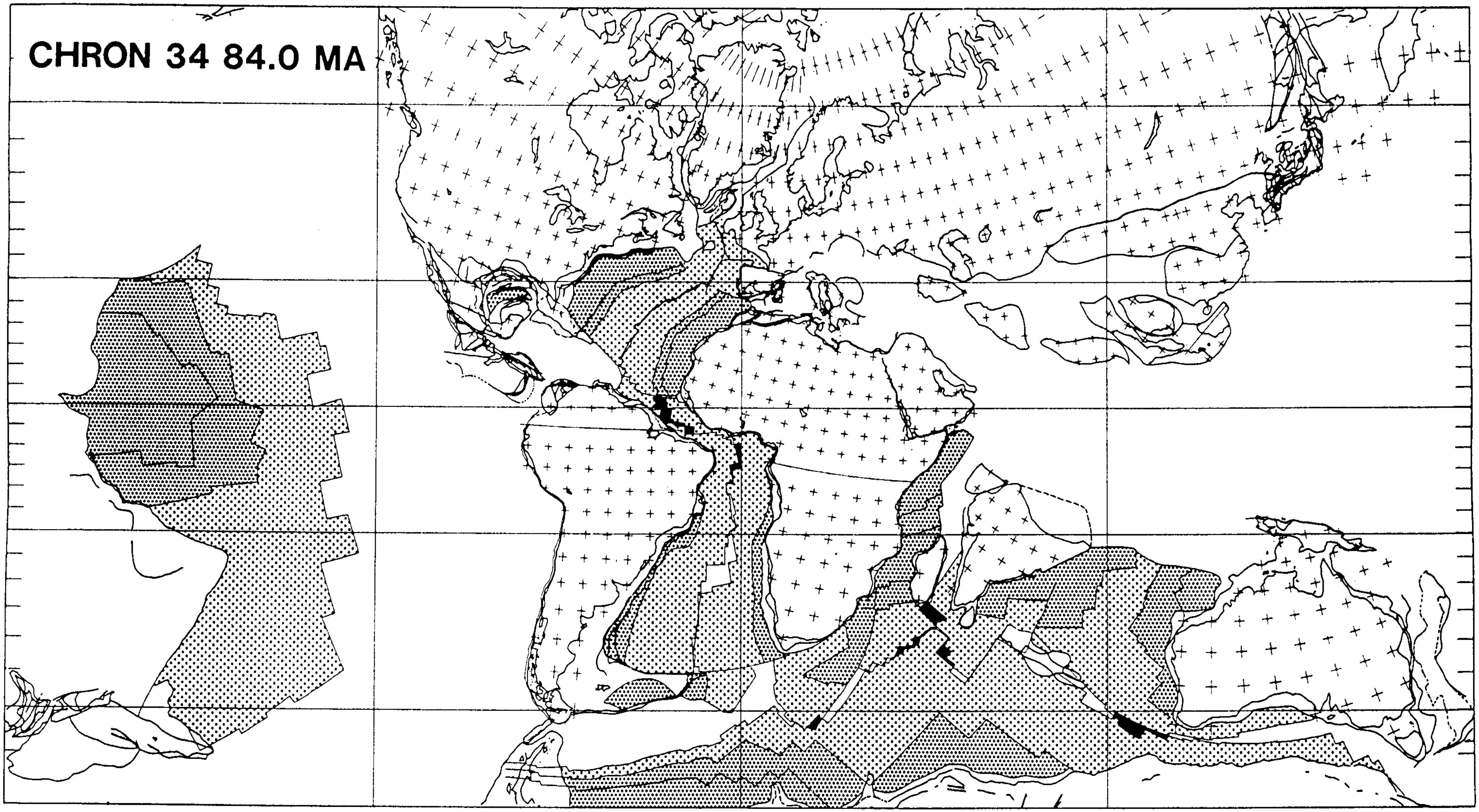


Figure 9.

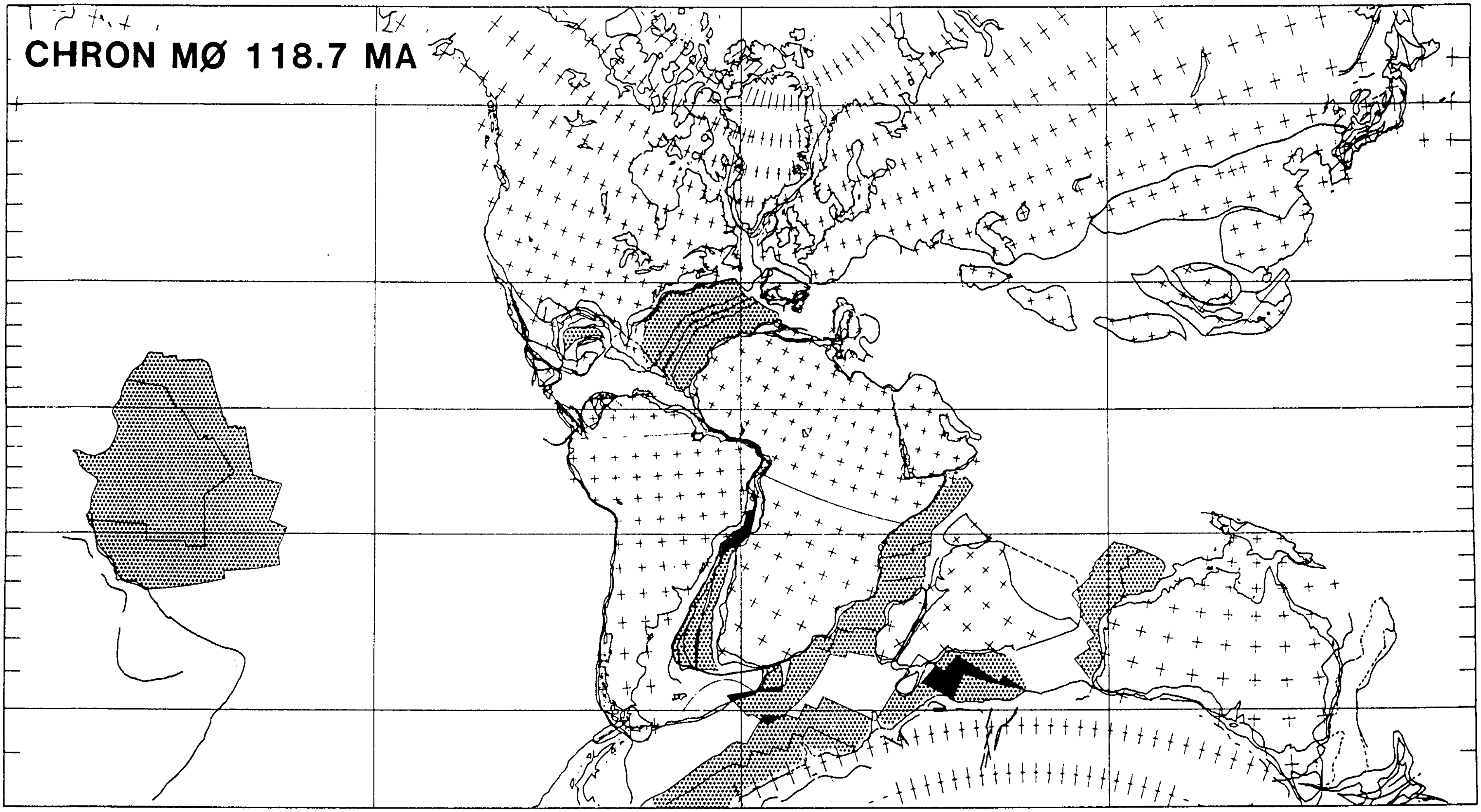
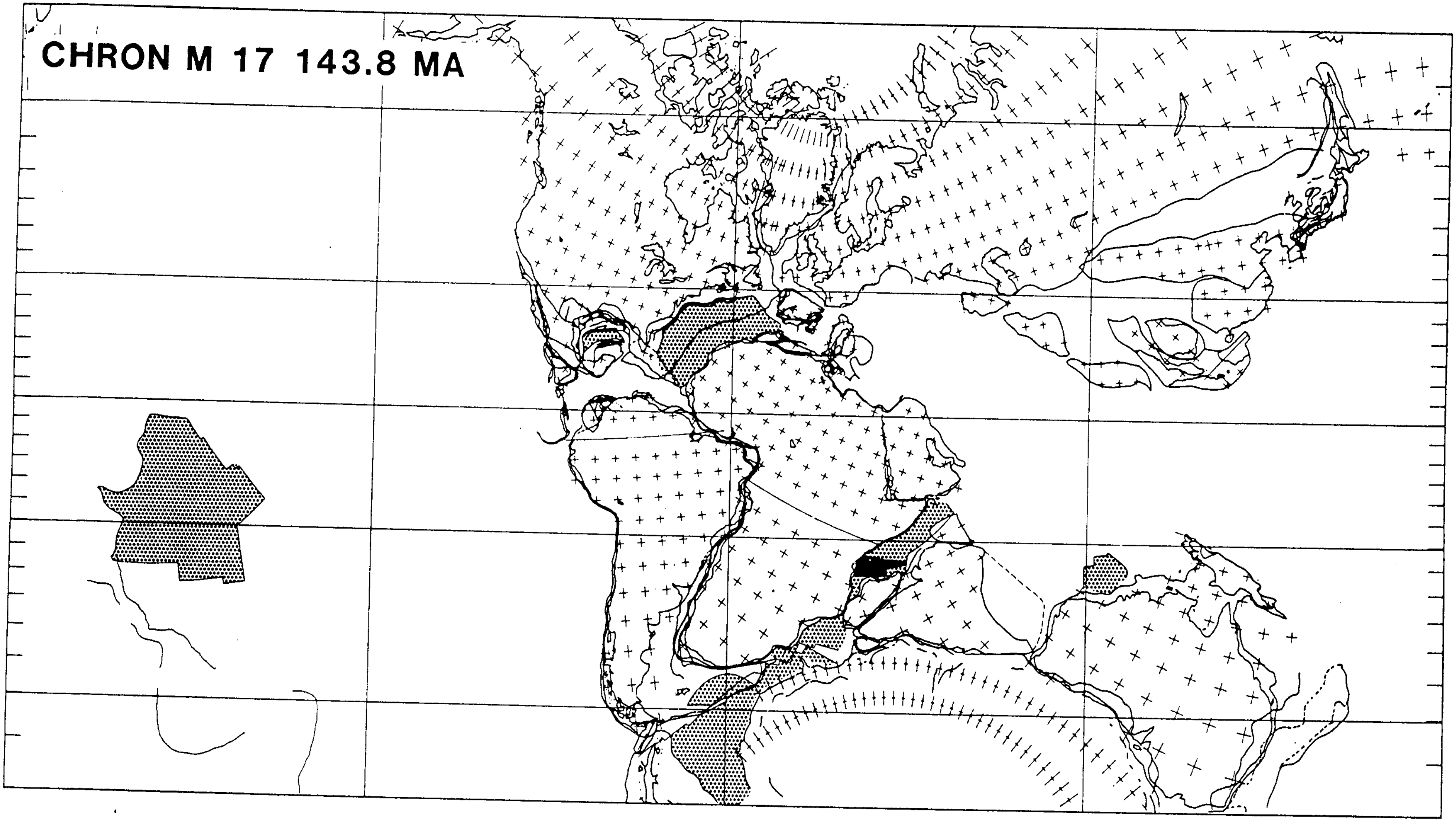


Figure 10.



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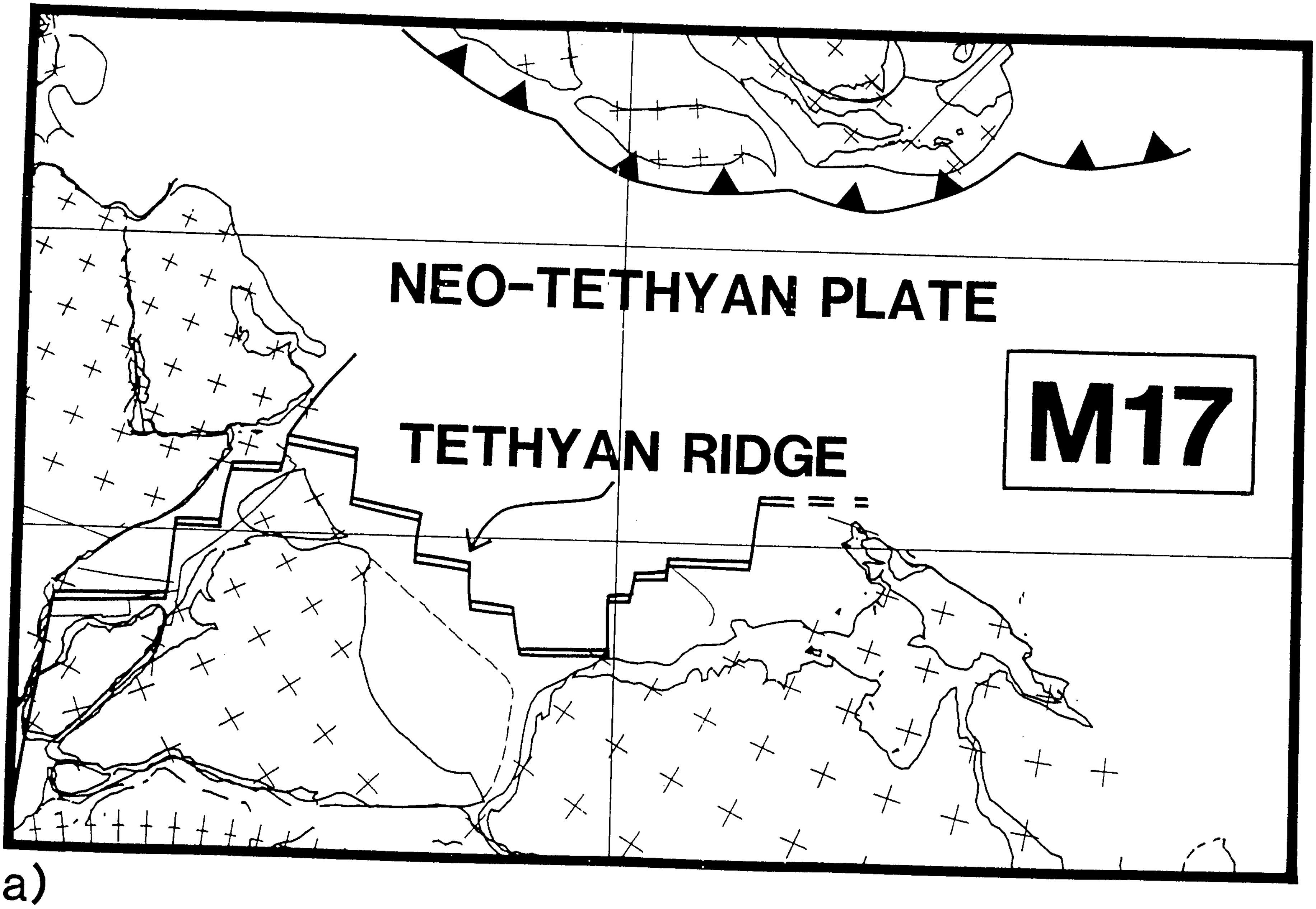


Figure 12.

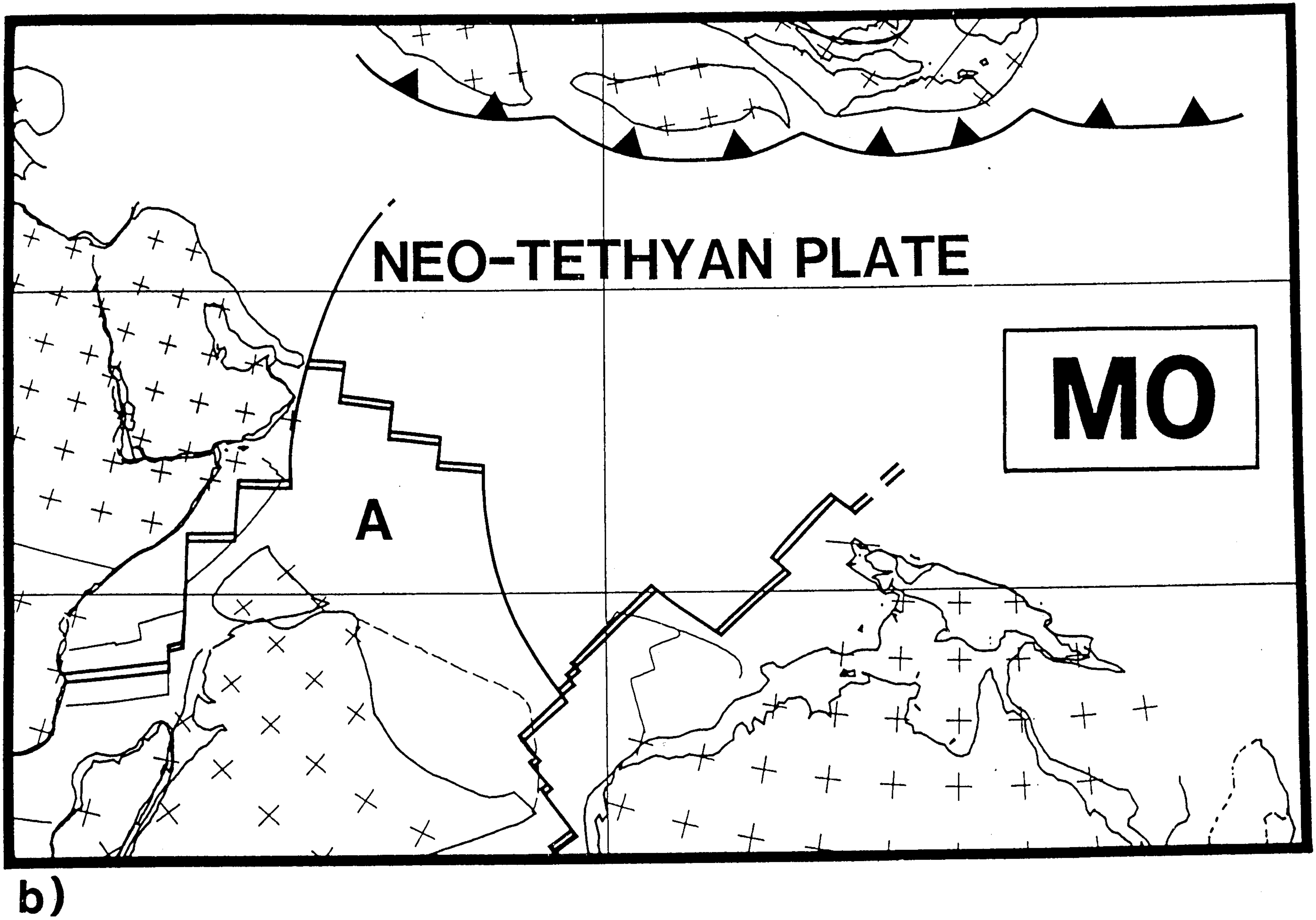
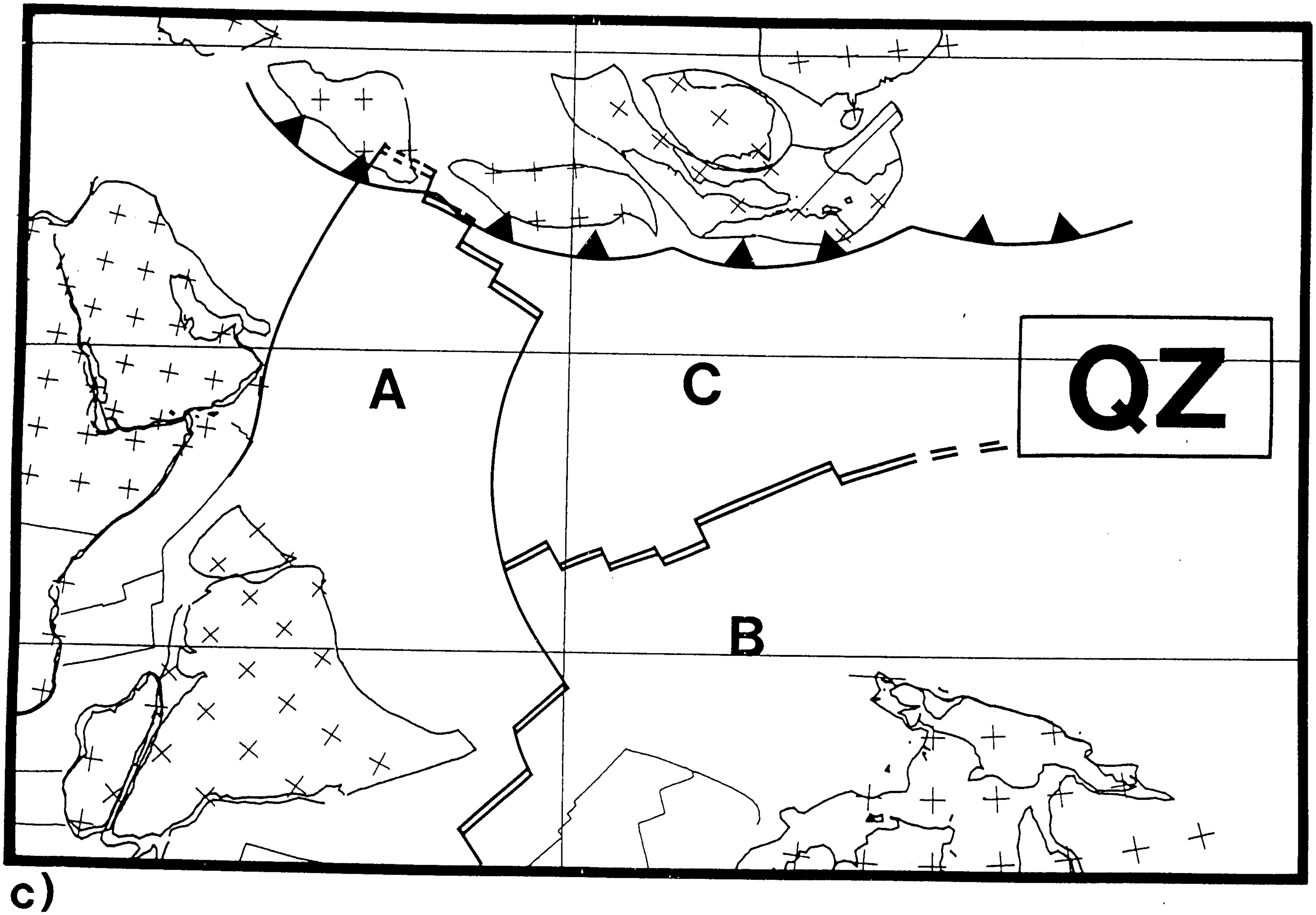


Figure 12.



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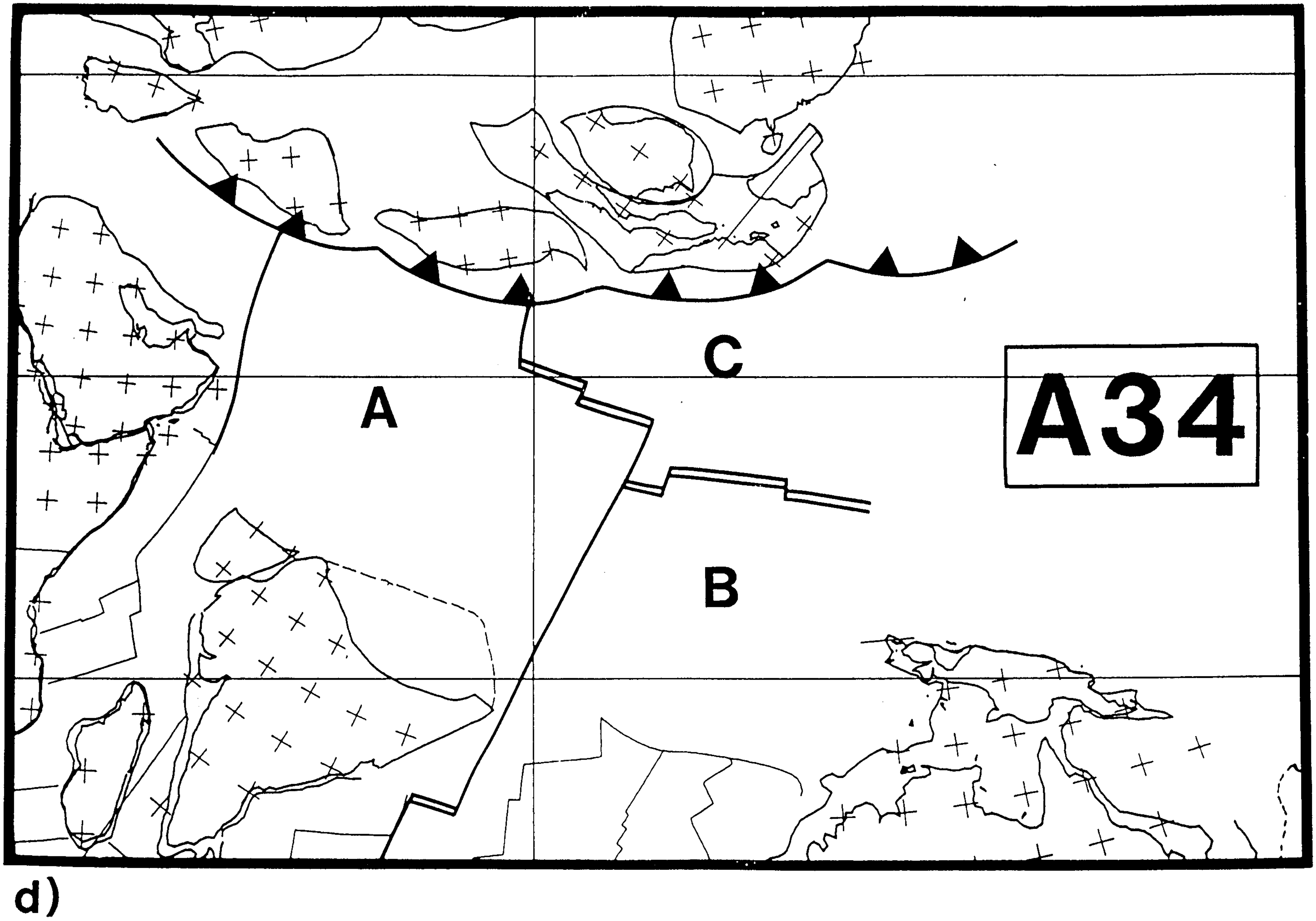

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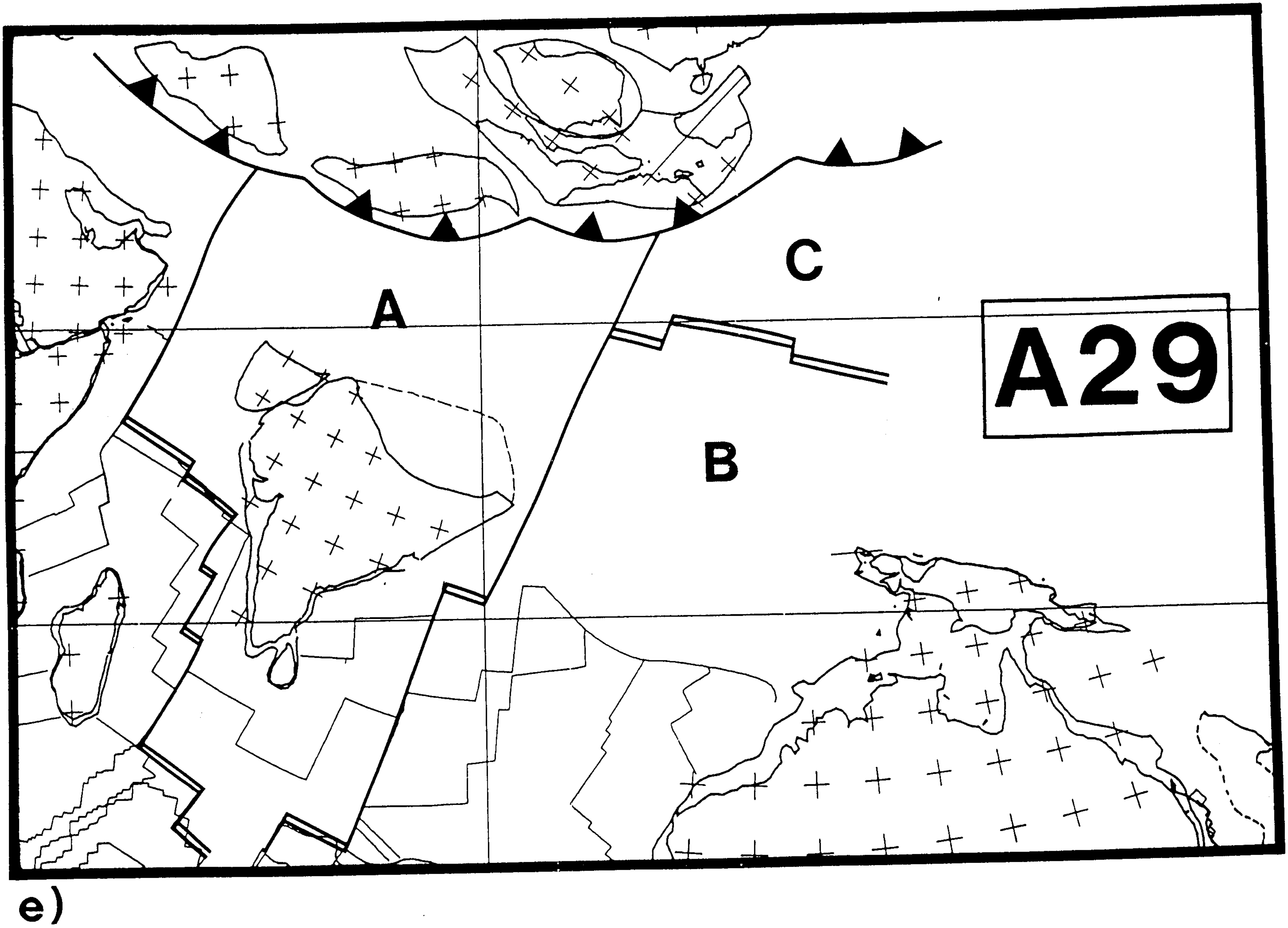

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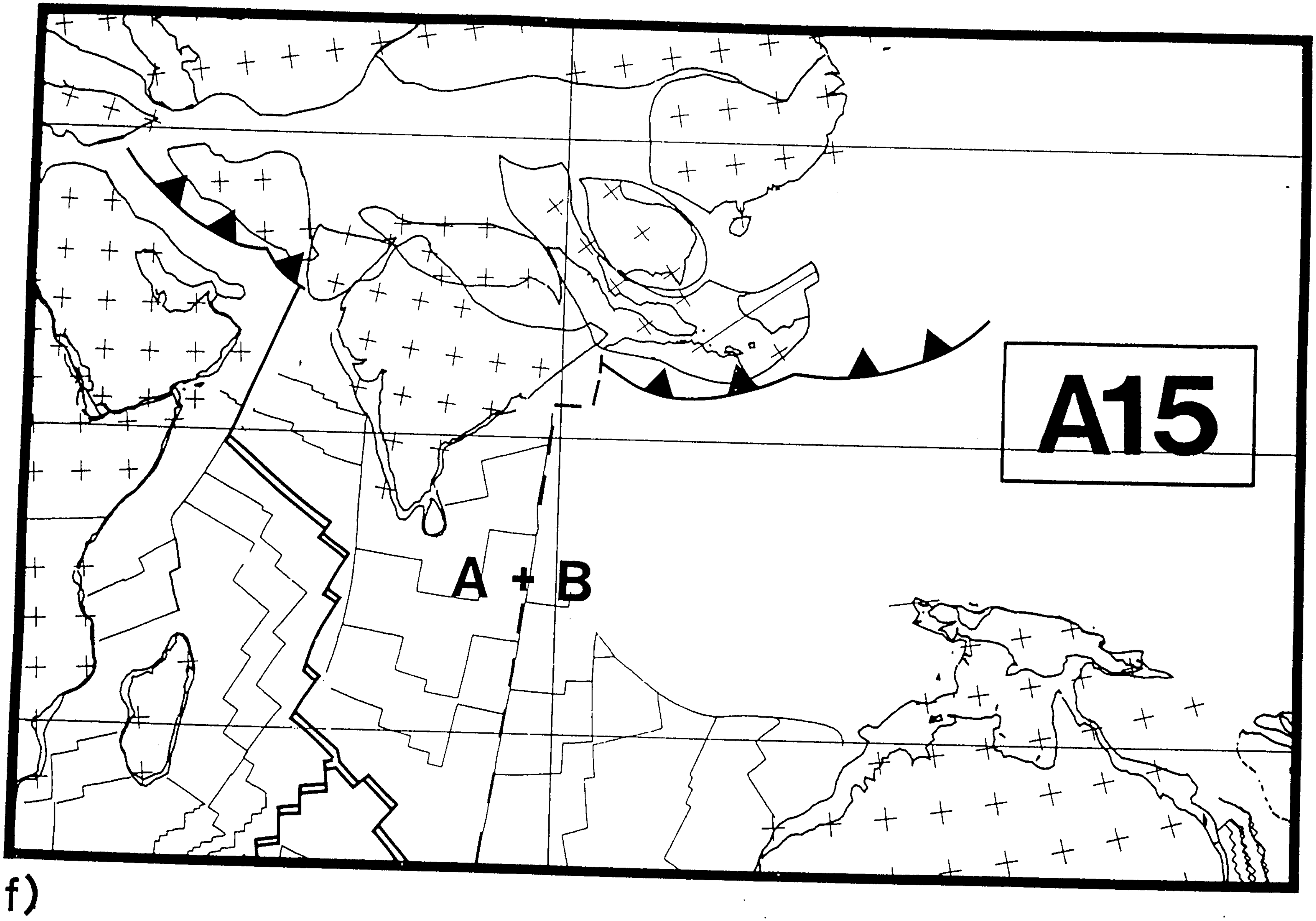

Figure 12.