NSG-7610

HOTSPOTS, POLAR WANDER, MESOZOIC CONVECTION AND THE GEOID

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October 27, 1981
Revised November 6, 1981
Revised November 10, 1981

Abstract

The geoid bears little relation to present tectonic features of the earth other than trenches. The Mesozoic supercontinent of Pangea, however, apparently occupied a central position in the Atlantic-African geoid high. This and the equatorial Pacific geoid high contain most of the world's hotspots . The plateaus and rises in the western Pacific formed in the Pacific geoid high and this may have been the early Mesozoic position of Pacifica, the fragments of which are now the Pacific rim portions of the continents. Geoid highs which are unrelated to present subduction zones may be the former sites of continental aggregations and mantle insulation and, therefore, hotter than normal mantle. The pent-up heat causes rifts and hotspots and results in extensive uplift, magmatism, fragmentation and dispersal of the continents and the subsequent formation of plateaus, aseismic ridges and seamount chains. Convection in the uppermantle would then be due to lateral temperature gradients as well as heating from below and would be intrinsically episodic.

The Earth's largest positive geoid anomalies are associated with subduction zones and hotspots and bear no simple relationship to other present-day tectonic regions such as continents and ridges. When the subduction-related geoid highs are removed from the observed field the residual geoid shows broad highs over the central Pacific and the eastern Atlantic/African regions.[1,2] Like the total geoid the residual geoid does not reflect the distribution of continents and oceans and shows little trace of the ocean ridge system. Geoid highs, however, correlate with regions of anomalously shallow ocean floor and sites of extensive Cretaceous volcanism.

The Atlantic-African geoid high extends from Iceland through the north Atlantic and Africa to the Kerguelen plateau and from the middle of the Atlantic to the Arabian penninsula and western Europe. Most of the Atlantic, Indian Ocean, African and European hotspots are inside this anomaly. Iceland, Trindade, Tristan, Kerguelen, Reunion, Afar, Eiffel and Jan Mayan form the 20 meter boundary of the anomaly and appear to control its shape. The Azores, Canaries, New England seamounts, St. Helena, Crozet and the African hotspots are interior to the anomaly.

Although the geoid high cuts across present-day ridges and continents there is a remarkable correspondance of the predrift assemblage of continents with both the geoid anomaly and hotspots, Figure 1. Reconstruction of the mid-Mesozoic configuration of the continents reveals, in addition, that virtually all of the large shield areas of the world are contained inside the geoid high. These include the shield areas of Canada, Greenland, Fennoscandia, India, Africa, Antarctica and Brazil. Most of the Phanerozoic platforms are also in this area, the main exception being the Siberian platform.

The area inside the geoid high is also characterized by higher-than-normal elevations, for example in Africa,[3] the north Atlantic and the Indian Ocean southeast of Africa. This holds true also for the axial depth of oceanic ridges. Most of the continental areas were above sea-level from the Permo-Carboniferous through the Triassic, at which time there was subsidence in eastern North and South America, central and southern Africa, Europe and Arabia.[5] The widespread uplift, magmatism, breakup and initial dispersal of the Pangean landmass apparently occurred while the continents were centrally located with respect to the present geoid anomaly. The subsequent motions of the plates, by and large, were and are directed away from the anomaly. This suggests that the residual geoid high, hotspots, the distribution of continents during the late Paleozoic and early Mesozoic and their uplift and subsequent dispersal and subsidence are all related. The shields are regions of abnormally thick lithosphere. The thickest lithosphere is in eastern and central North America, northeastern South America, northwestern and central Africa and northern Siberia.[7] These regions were all within the area of Figure 1 at 200 My, and, possibly, at 350 m.y. as well.

The area in Fig. 1 experienced exceptional magmatism during the Mesozoic. The great flood basalts of Siberia and South Africa were formed during the Triassic and Jurassic, possibly at the sites of the Jan Mayen and Crozet hotspots. The plateau basalt provinces of Southeast Greenland and Brazil were formed during the Cretaceous, possibly at the sites of the Iceland and Tristan or Trindade hotspots.[6] The Deccan Traps in India were also formed in the Cretaceous, presumably at the Reunion hotspot. The Walvis Ridge and the Rio Grande Rise are mainly on Mesozoic crust. A large part of the Pacific also experienced extensive on- and off-ridge volcanism in the Cretaceous.[12] This extensive ridge and hotspot volcanism apparently reflects itself in a rapid rise in sea-level during the Jurassic and Cretaceous. If sea-level can be used as a guide to the volume of the ocean basins[8] then the end of the Cretaceous to the end of the Oligocene was a period of less intense oceanic volcanism and subsidence of the oceanic and continental crust. Sea-level variations may therefore indicate that the thermal and geoid anomalies formed in the Paleozoic and have attentuated since the early Mesozoic.

Much of the Pacific rim appears to be accreted terrain which originated in the Pacific.[27] The possibility of a continent centrally located in the Pacific, Pacifica, has been discussed for some time,[9] but its location has been an enigma and its size uncertain. The central Pacific geoid anomaly may mark the early Mesozoic location of the anomalous terrain and the site of extensive Cretaceous ridge crest and midplate volcanism. If so, Pacifica is a much larger continent and in quite a different place than has been previously discussed.[27]

Paleomagnetic and other data indicate that various blocks of Asia such as Kolyma, Sikhote Alin, Sino-Korea, Yangtze, Southeast Asia and Japan have moved northward by up to 32° since the Permian.[10] It is unlikely that they were in the vicinity of Australia or associated with Gondwana[10] and a central Pacific location is likely. Part or all of

Alaska and northwestern North America were also far south of their present positions in the Permian.[11] The same may be true of California, Mexico, Central America and other accreted terrain in the Pacific rim continents. A possible location of these continental fragments, relative to the Pacific geoid anomaly, is shown in Fig. 3.

The central Pacific residual geoid high (> 20 meters) extends from Australia to the East Pacific Rise and from Hawaii to New Zealand. The western part of the residual geoid overlaps the subduction zones of the southwest Pacific and may be eliminated by a different slab model. The actual residual geoid anomaly may therefore be more equidimensional and is perhaps centered over the polynesian plume province in the central Pacific. In any case it encompasses most of the Pacific hotspots and is approximately antipodal to the Atlantic-African anomaly. Fig. 2 shows the geoid anomalies superposed on a hypothetical Triassic assemblage of the continents.

The western Pacific contains numerous plateaus, ridges, rises and seamounts which have been carried far to the northwest from their point of origin. The Ontong-Java plateau for example, presently on the equator, was formed at 33-40°S in the mid-Cretaceous.[13] The Hess rise, Line Islands ridge and Necker ridge were formed in the Cretaceous on the Pacific, Farallon and Phoenix ridge-crests[12] which were, at the time, in the eastern Pacific in the vicinity of the polynesian seamount province. This ridge-crest volcanism was accompanied by extensive deep-water volcanism[12] and, possibly, rapid seafloor spreading.[14] The Caribbean and Bering Seas may have formed at the same location and carried northward on the Farallon and Kula plates. It is significant that the Caribbean and the anomalous regions in the Pacific have similar geophysical and geochemical characteristics.[15]

The Pacific geoid high also has anomalously shallow bathymetry, at least in the eastern part.[3,4] This shallow bathymetry extends from the East Pacific Rise to the northwest Pacific in the direction of plate motion, and includes the central and southwest Pacific hotspots. The extensive volcanism in the central western Pacific between about 70 to 120 My[12,15] occurred about 60^{o} to 100^{o} to the southeast, in the hotspot frame. This would place the event in the vicinity of the southeastern Pacific hotspots and the eastern part of the geoid and bathymetry anomaly. This suggests that the anomaly dates back to at least early Cretaceous. A similar thermal event in the Caribbean[16] may mean that it was also in this region in the Cretaceous, particularly since the basalts in the Caribbean are similar to those in the western Pacific.[15]

Going back even further are the Triassic basalts in Wrangellia[11] of northwestern North America and the Permian greenstones in Japan,[9] both of which formed in equational latitudes and subsequently drifted to the north and northwest respectively. They may record the initial rift stages of continental crust.[9] We speculate that they also formed in the Pacific geoid high.

We propose that episodicity in continental drift, polar wander, sea-level variations and magmatism is due to the effect of thick continental lithosphere on convection in the mantle. The supercontinent of Pangea insulated a large part of the mantle for more than 150 My. The excess heat caused uplift by thermal expansion and partial melting and, eventually, breakup and dispersal of Pangea. A large geoid high is generated by this expansion and, if this is the dominant feature of the geoid, the spin axis of the Earth would change so as to center the high on the equator, much as it is today. The continents stand high while they are within the geoid high and subside as they drift off.

At 100 My BP Europe, North America and Africa were relatively high-standing continents.[17] This was after breakup commenced in the North Atlantic but before significant dispersal from the pre-breakup position. North America suffered widespread submergence during the late Cretaceous while Africa remained high.[17] Europe started to subside at about 100 My. This is consistent with North America and Europe drifting away from the center of the geoid high while Africa remained near its center, as it does today.

The association of the Atlantic-Africa geoid high with the former position of the continents and the plateau basalt provinces with currently active hotspots suggests that Mesozoic convection patterns in the mantle still exist, as proposed by Menard.[18] The mid-Atlantic and Atlantic-Indian ridges and the Atlantic, African and Indian ocean hotspots and the East African rift are regions where heat is being efficiently removed from the uppermantle. If geoid anomalies and hotspots are due to a long period of continental insulation and if these regions had higher-than-normal heat flow and magmatism for the past 200 My, then we might expect that these features will wane with time.

Horizontal temperature gradients can drive continental drift.[20,21,22,23,29]. The velocities decrease as the distance increases away from the heat source and as the thermal anomaly decays due to extensive magmatism. The geoid high should also decay for the same reasons. Thick continental lithosphere then insulates a new part of the mantle and the cycle repeats. Periods of rapid polar motion and continental drift follow periods of continental stability and mantle insulation.

The relatively slow motion of the continents[19] or the pole[24] during the Permian and the relative stability of sea-level during this period suggests that the geoid anomalies had essentially developed at this time. Continental drift velocities[19] and sea-level[8] changed rapidly during the Triassic and Jurassic. This we interpret as the start of extensive rift and hotspot magmatism and the start of the decay of the anomaly.

The rotation axis was apparently stable from about 200 to 80 My[6] but has shifted with respect to the hotspot reference frame for at least the last 65 My.[26] This shift could represent a growth of the equatorial regions of the geoid highs, a decay of the South Pacific or North Atlantic portions of the high due to extensive ridge axis and hotspot volcanism or a reconfiguration of the world's subduction zones.

Chase[1] concluded that the lack of correlation of the large geoid anomalies to plate boundaries requires that they reflect a deep convective flow regime in the mantle which is unrelated to plate tectonics. The correspondence of the Atlantic-African anomaly with the Mesozoic continental assemblage and of the central Pacific anomaly with extensive Cretaceous volcanism in the Pacific is remarkable and suggests that the anomalies are of shallow origin and that they affect the motions of the plates. Even more interesting is the possibility that the continents themselves were responsible for the geoid highs by preventing extensive ridge-type volcanism.

It is difficult to separate true polar wander and the apparent wander due to continental drift. In the present model they are intimately related. If ridge volcanism is precluded for an extensive period of time, as appears to have been the case in the mantle under Pangea during the early Mesozoic, the mantle will warm up and/or partially melt. In either case a geoid anomaly will develop. This anomaly will affect convection and plate motions in a manner previously suggested[20,23] and will also affect the rotation axis of the Earth.[25] Since the thermal anomalies appear to be long-lived and it takes a long time to establish a new thermal regime, major shifts of the rotation axis due to this mechanism will be infrequent and gradual.

Goldreich and Toomre[25] have shown that density inhomogeneities caused by convection in the mantle will control the orientation of the spin axis and that large shifts of the pole, i.e., true polar wander are to be expected in a dynamic Earth. The present orientation of the pole apparently bears no relationship to the present distribution of continents, ridges or trenches.[25] On the other hand, the geoid bears a close relationship to the present distribution of hotspots and to the former distribution of continents and areas of extensive Cretaceous ridge and plateau volcanism.

Discussion

The Atlantic-African geoid high appears to represent the location of the Mesozoic continental aggregation of Pangea. It is therefore natural to suggest that the Pacific geoid high represents the previous location of the fragments which have accreted onto the Pacific rim continents. These fragments may include all or parts of southeast Asia, Siberia, the Bering Sea, Alaska, Western North America, Mexico and Central America, the Caribbean and older terrain in Western South America. If Pacifica also included China and East Antarctica it would approach Gondwana in size. A continental aggregation causes heating of the underlying mantle by preventing ridge-type volcanism. This heating, in turn, causes thermal expansion, partial melting, uplift and extensional stress in the continental lithosphere. The horizontal temperature gradient in the uppermantle then drives the plates away from the thermal anomaly. Extensive ridge-axis and intraplate magmatism can be expected in the regions formerly occupied by continental lithosphere.

If our conjecture about the relationship between geoid highs and the former position of continents is correct then we would conclude that there were two large antipodal continental aggregations in the Permian - Pangea and Pacifica. Pangea was composed of most of North and South America, Europe, India, Africa and, probably, the cratons of Australia and East Antarctica. We tentatively assume that much of western North and South America, Central America, Asia and West Antarctica were part of Pacifica. The antipodal supercontinents were presumably formed by a previous episode of continental drift which swept buoyant material away from a prior configuration of thermal and geoid highs. Using sea-level as a guide, with high sea-level indicating rifting and extensive sea-floor volcanism, the Pangea and Pacifica continents were probably stable from 300 to 150 My ago and the previous continental assemblages were dispersing between 500 and 350 My. This agrees with the paleomagnetic and geological evidence.[28]

ACKNOWLEDGEMENTS

I thank Brad Hager and Henri Nataf for reviewing the manuscript, and Lynn Sykes for a series of stimulating discussions. This work was supported by the National Aeronautics and Space Administration Grant No. NSG-7610; Contribution No. 3710, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, 91125.

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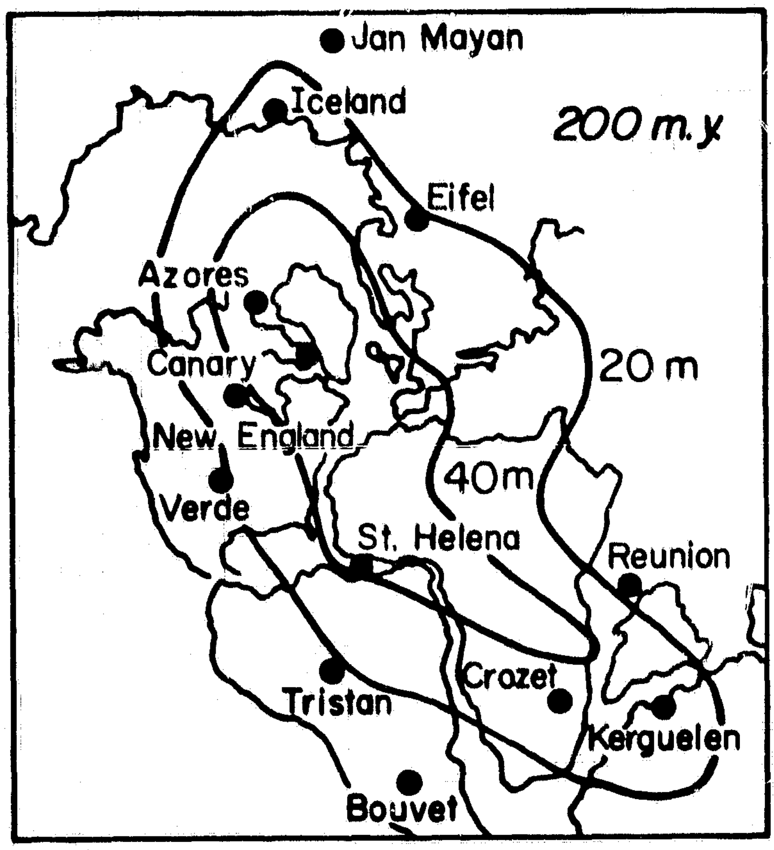
Figure Captions

Figure 1. The Jurassic configuration of the continents, based on Morgan's hotspot-based reconstruction, superposed on the Atlantic-African residual geoid high.[1,2] Note that most of the stable shield areas are inside the 20 meter contour. Selected hotspots (•) are also shown.

Figure 2. Locations of the continents[5] during the Triassic. The dashed lines enclose regions of high elevation (> 20 meters) of the residual geoid.[1,2] Arrows show the subsequent directions of motion of the plates. The hatched regions are accreted terrains that were probably not part of Pangea. They may have come from the eastern part of the Central Pacific geoid high. Note the concentration of hotspots in the geoid highs. The centers of the geoid highs are almost exactly antipodal.

Figure 3. Possible locations of the Pacific rim microcontinents relative to the central Pacific geoid high. Relative locations of the eastern Asia landmasses from McElhinny et al.[10] These microcontinents may in turn be made up of multiple smaller terrains but the present outlines are maintained for simplicity. China and East Antarctica may also have been part of this Pacific continent. This region of the Pacific was the site of extensive on- and off-axis volcanism in the Cretaceous[12] and the site of several triple junctions.[14] Parts of the Caribbean, Scotia, and Bering Seas

and the western Pacific plateaus may have formed in this region after dispersal of the protocontinent.


Jan Mayan
Iceland
200 m.y.
Eifel
Azores
Canary
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New England
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Verde
St. Helena
Reunion
Crozet
Tristan
Kerguelen
Bouvet

Fig. 1

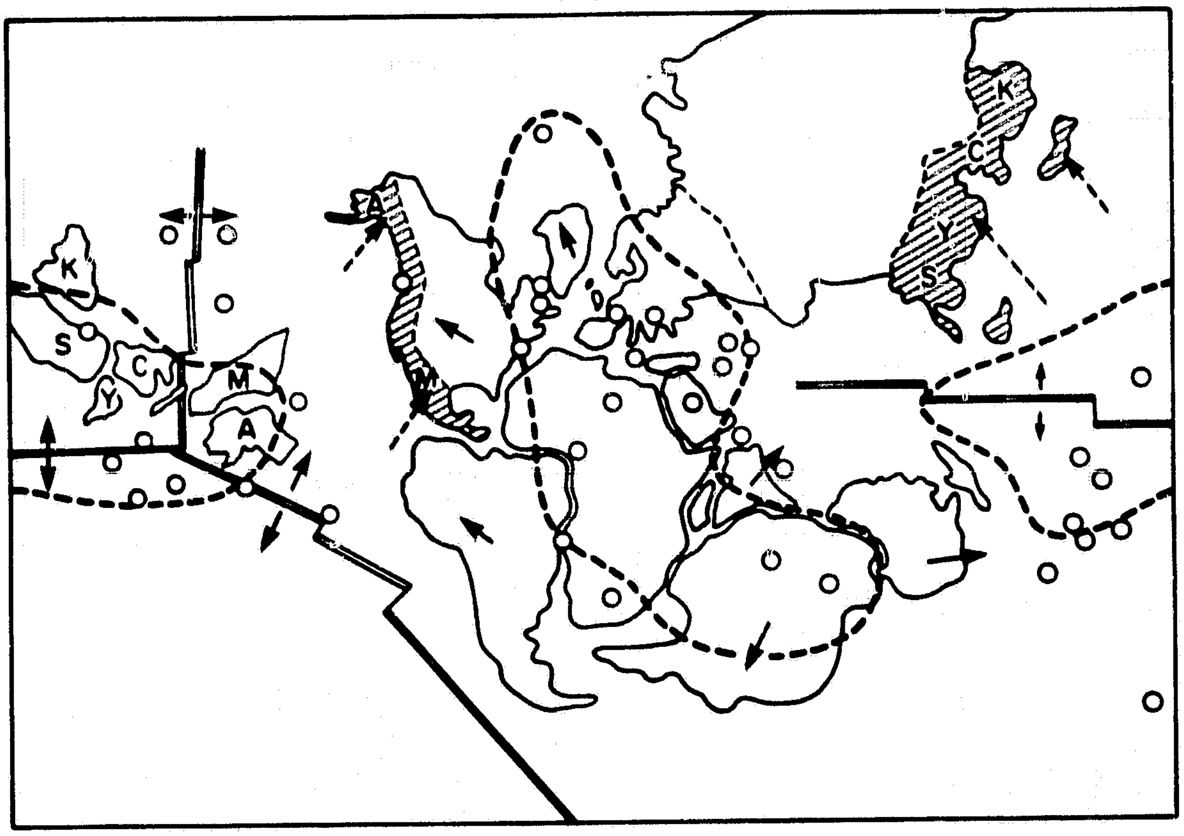
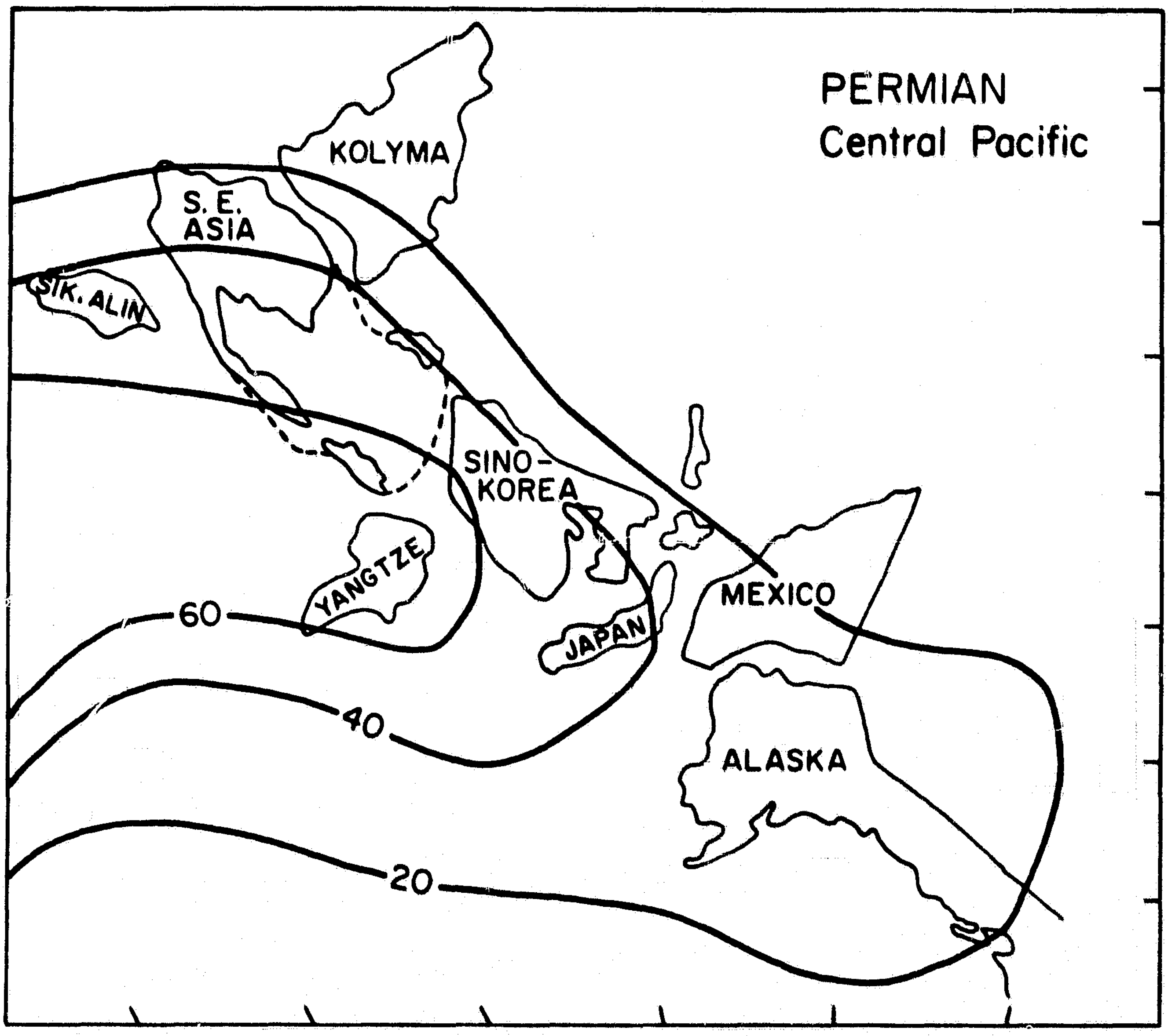


Fig. 2


PERMIAN
Central Pacific
KOLYMA
S. E.
ASIA
SIK. ALIN
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60
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Fig. 3