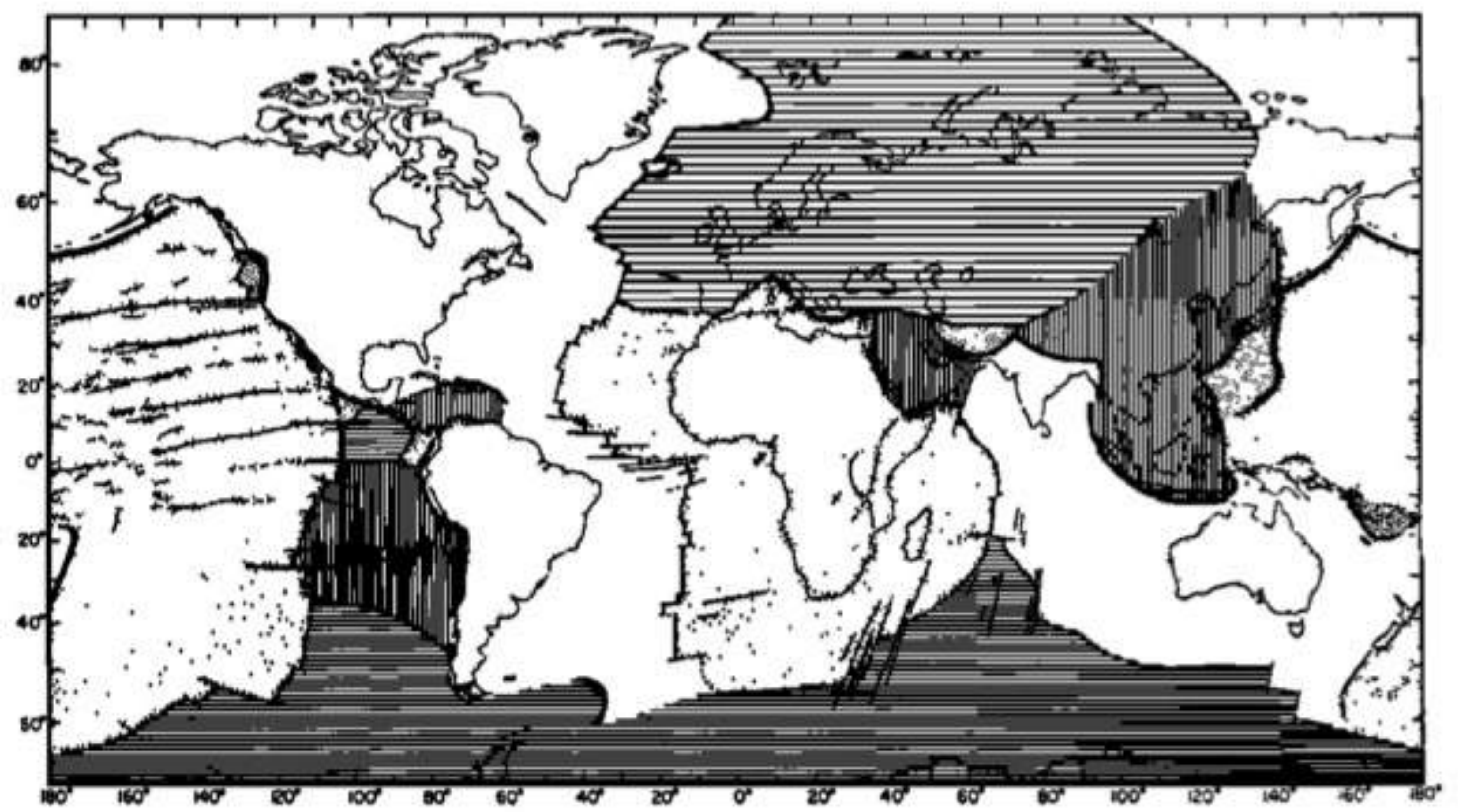
50 years of plate tectonics

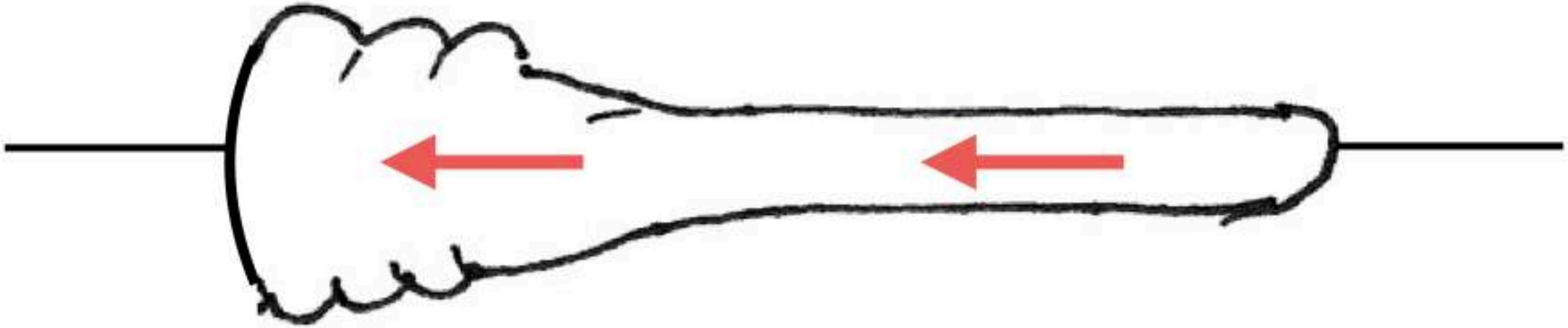


Jason Morgan
Princeton University
Harvard University

Collège de France
25 June, 2018

How are mountains made? — Continental Drift

“A ship of Sial sailing through a sea of Sima”

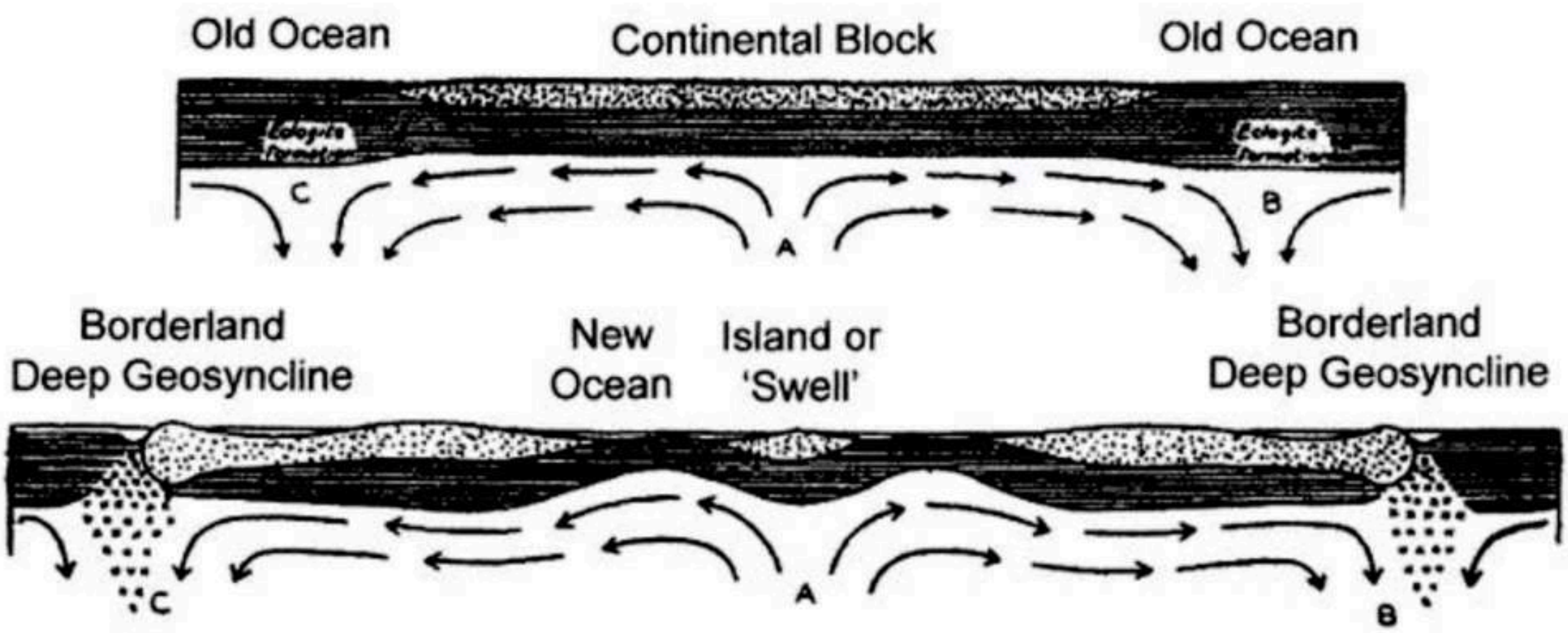


Crumpled leading edge

Quiet trailing edge

Sial = silica - aluminum (crustal rocks)
Sima = silica - magnesium (basaltic rocks)

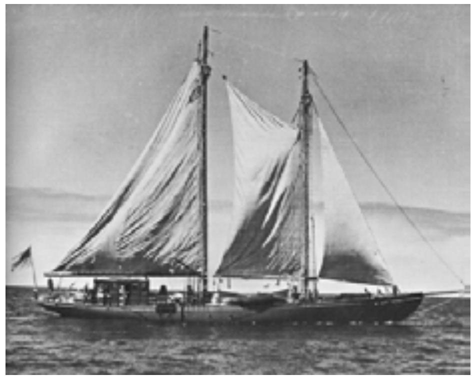
Arthur Holmes (1929) - - Convection currents in mantle drives continental drift



Arthur Holmes hypothesized that large-scale, **thermally driven convection** in the mantle would result in new oceanic magma-crust (and therefore new oceans) being generated along an oceanic "swell", and that this process would drive the horizontal displacement of continents. He published this in 1929, long before the application of paleomagnetism (and the recognition of magnetic pole reversals) to ocean basins. In retrospect, his hypothesis was prescient, and while some of the terminology has changed, his vision has mostly stood the test of time. The horizontal translation of ocean basins would later be referred to as **Sea Floor Spreading**.

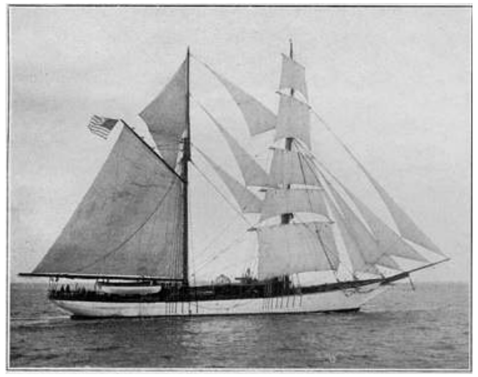
U. S. oceanographic fleet

from ~1900 to 1940



E. W. Scripps (Scripps Inst. Oceanography)

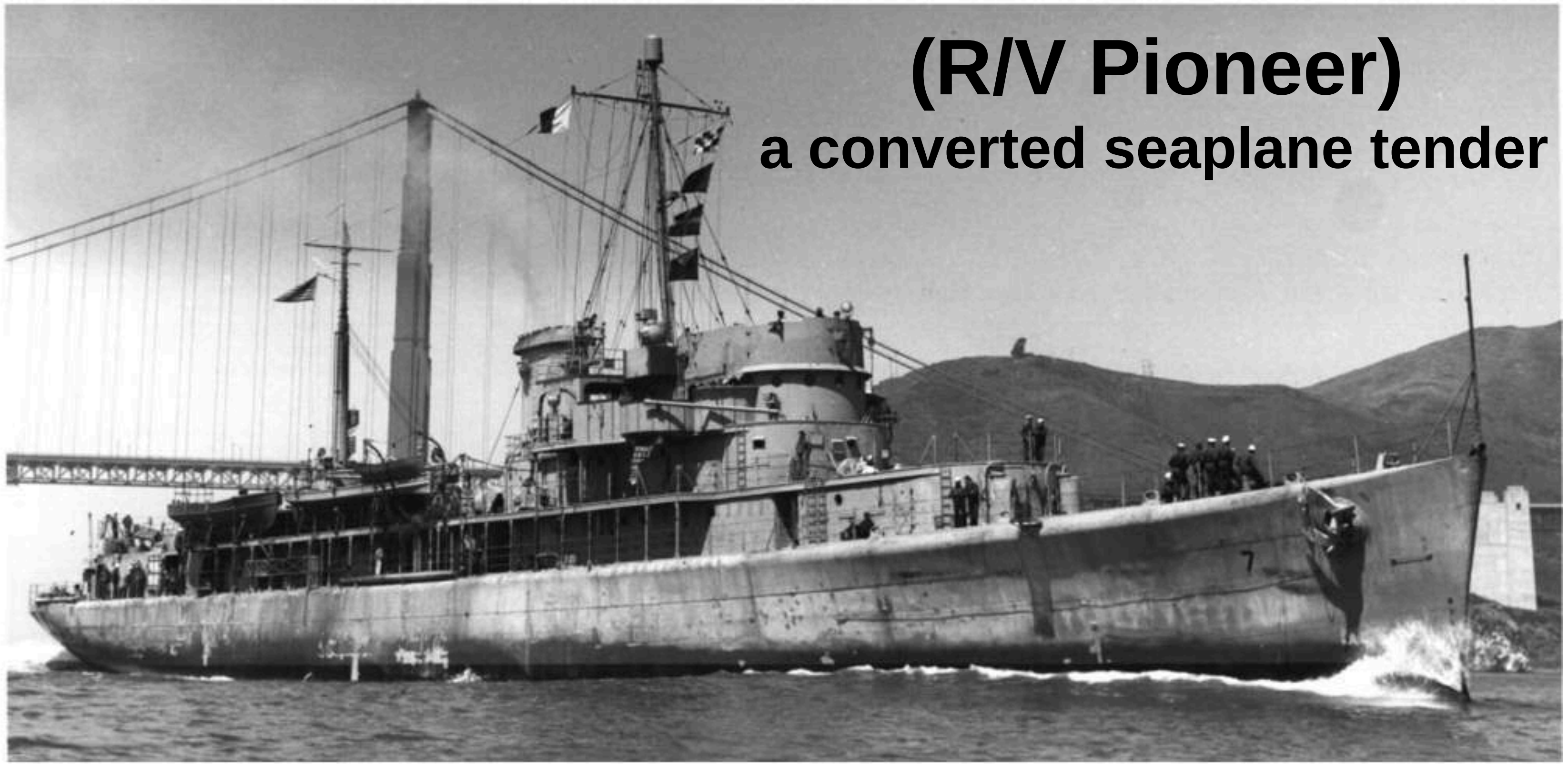
Atlantis (Woods Hole Oceanographic Inst.)



Carnegie (Carnegie Inst. Washington)

(last cruise of the Carnegie, 1929)

by 50's, there were ~ 20 ships



(R/V Pioneer)

a converted seaplane tender

What was learned in the 1950's (with many ships, many new techniques)

Bathymetry –	**Many topographic features discovered: seamount chains, fracture zones, mid-ocean rift system.**
Seismic Refraction –	**Oceanic crust very different from continental crust – a very uniform 5-to-6 km, not like variable continental crust.**
Seismic Reflection –	**Oceanic sediments generally quite thin, almost none near the mid-ocean ridges.**
Piston cores, dredges –	**No samples of Precambrian or Paleozoic materials recovered from oceans, only Cretaceous and younger.**
Heatflow –	**Heatflow of oceanic crust is the about same as continental crust; not much less because of no thick radioactive crust .**
Earthquakes –	**Oceanic earthquakes (all shallow events) are highly correlated with the mid-ocean ridge system.**
Magnetics –	**Unlike the knotty/confused pattern of continental magnetic surveys, oceanic anomalies have long, linear patterns.**

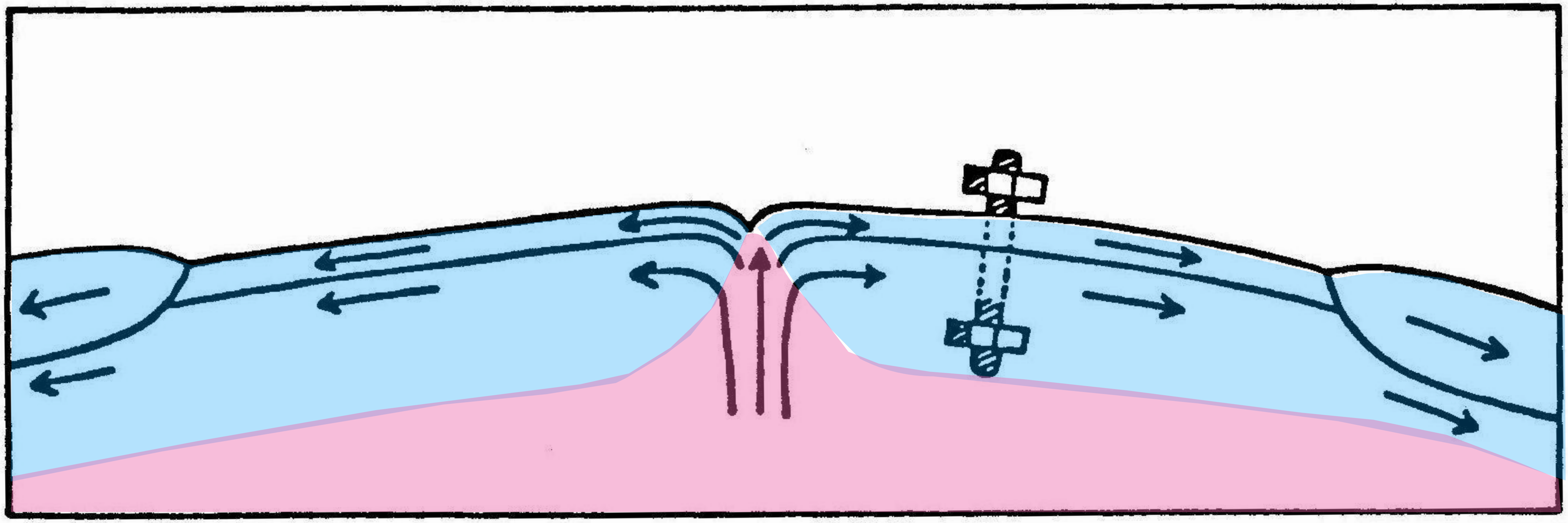
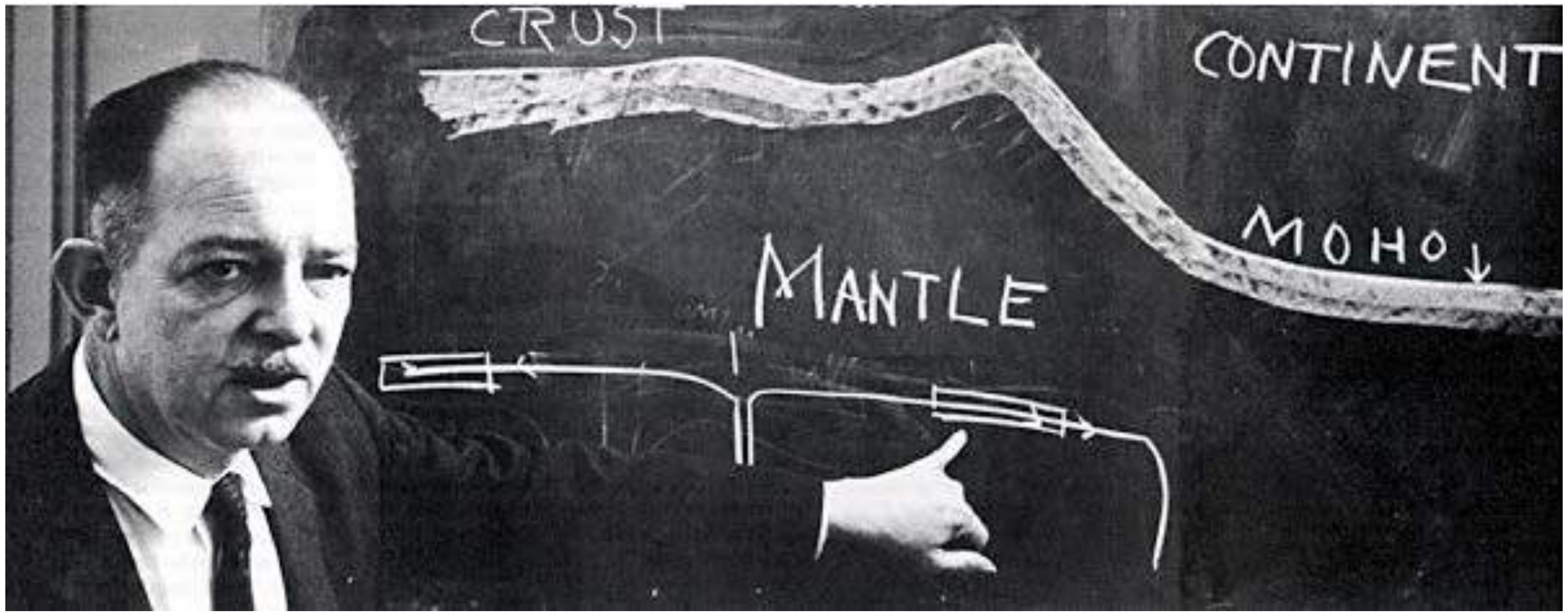


Figure 123. The crust and mantle move laterally away from the ridge-axis, both moving at the same velocity so there is no viscous drag effect. The trailing edges of continents are not deformed. The crust and mantle may be considered effectively to be bolted together. The continents move passively until their leading edges arrive at the site of the downward current. **(H. H. Hess)**



"A more acceptable mechanism is derived for continental drift whereby continents ride passively on convecting mantle instead of having to plow through oceanic crust." (Hess, 1960)

To me, the most remarkable thing about Hess's paper is after 18 pages of general discussion and 12 cartoons (only 3 showing any data) summarizing the known facts of the ocean floor, he sticks his neck out and makes a list of 19 specific tests of this new model.

RECAPITULATION

The following assumptions were made, and the following conclusions reached:

✓ (1) The mantle is convecting at a rate of 1 cm/yr.

✓ (2) The convection cells have rising limbs under the mid-ocean ridges.

✓ (3) The convecting cells account for the high heat flow and topographic rise.

1/2 (4) Mantle material comes to the surface on the crest of these ridges.

✗ (5) The oceanic crust is serpentinized peridotite, hydrated by release of water from the mantle over the rising limb of a current. In other words it is hydrated mantle material.

✗ (6) The uniform thickness of the oceanic crust results from the maximum height that the 500°C isotherm can reach under the mid-ocean ridge.

✓ (7) Seismic velocities under the crests of ridges are 10-20% lower than normal, but become normal again on ridge flanks. This is attributed to higher temperature and intense fracturing, with cooling and healing of the fractures away from the ridge.

✓ (8) Mid-ocean ridges are ephemeral features having a life of 200 to 300 million years (the life of the convecting cell).

1/2 (9) The Mid-Pacific Mesozoic Ridge is the only trace of a ridge of the lost cycle of convection cells.

✓ (10) The whole ocean is virtually swept clean (replaced by new mantle material) every 300 to 400 million years.

✓ (11) This accounts for the relatively thin veneer of sediments on the ocean floor, the relatively small number of volcanic seamounts, and the present absence of evidence of rocks older than Cretaceous in the oceans.

✓ (12) The oceanic column is in isostatic equilibrium with the continental column. The upper surface of continents approaches equilibrium with sea level by erosion. It is thus axiomatic that the thickness of continents is dependent on the depth of the oceans.

✓ (13) Rising limbs coming up continental areas move the fragmented parts away from one another at a uniform rate so a truly median ridge forms as in the Atlantic Ocean.

✓ (14) The continents are carried passively on the mantle with convection and do not plow through oceanic crust.

✓ (15) Their leading edges are strongly deformed when they impinge upon the downward moving limbs of convecting mantle.

✓ (16) The oceanic crust, buckling down into the descending limb, is heated and loses its water to the ocean.

✓ (17) The cover of oceanic sediments and the volcanic seamounts also ride down the jaw crusher of the descending limb, are metamorphosed, and generally probably welded onto continents.

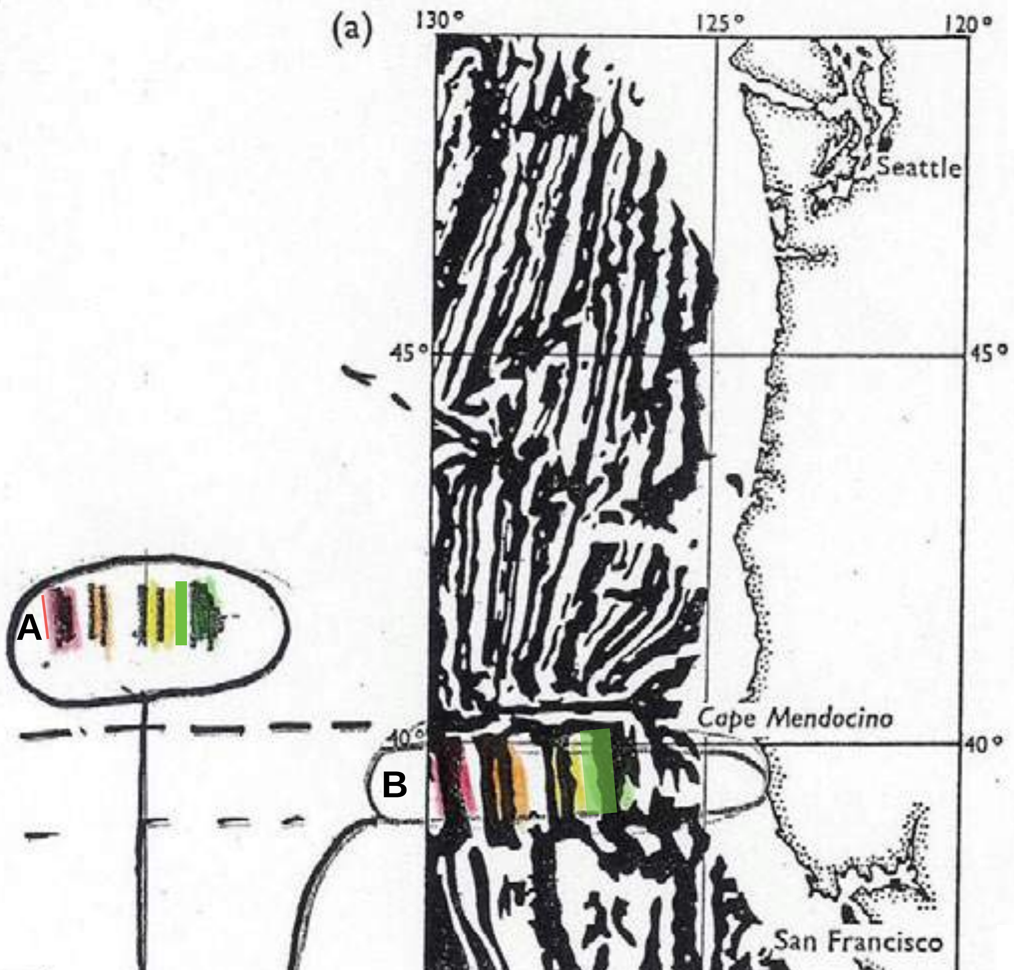
✓ (18) The ocean basins are impermanent features, and the continents are permanent although they may be torn apart or welded together and their margins deformed.

✓ (19) The Earth is a dynamic body with its surface constantly changing. The spherical harmonics of its topography show unexpected regularities, a reflection of the regularities of its mantle convection system and their secondary effects.

In this chapter the writer has attempted to invent an evolution for ocean basins. It is hardly likely that all of the numerous assumptions made are correct. Nevertheless it appears to be a useful framework for testing various and sundry groups of hypotheses relating to the oceans. It is hoped that the framework with necessary patching and repair may eventually form the basis for a new and sounder structure.

Magnetic anomaly discoveries - late 1950’s

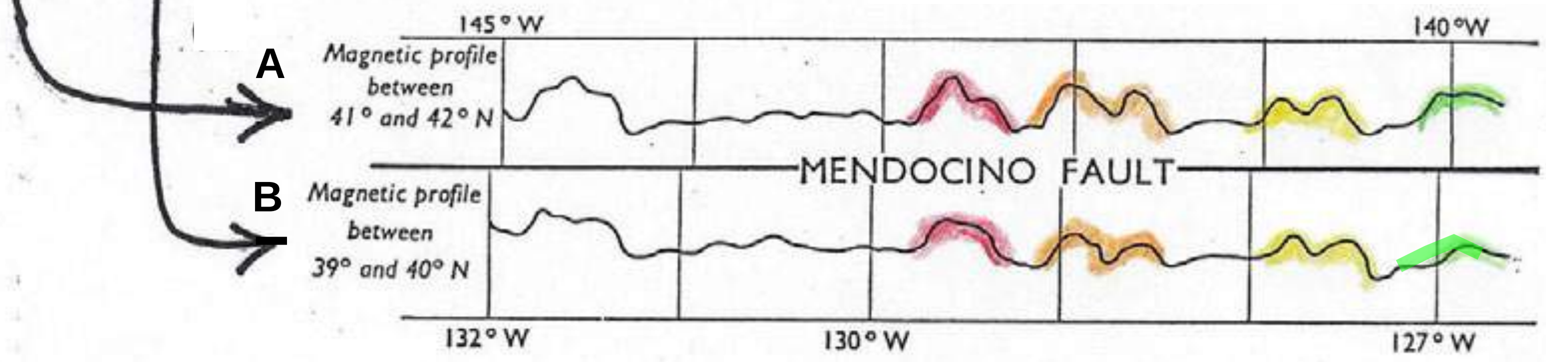
Raff and Mason (1958) make the first map of seafloor magnetic anomalies (from the survey of the R/V Pioneer off the west coast).



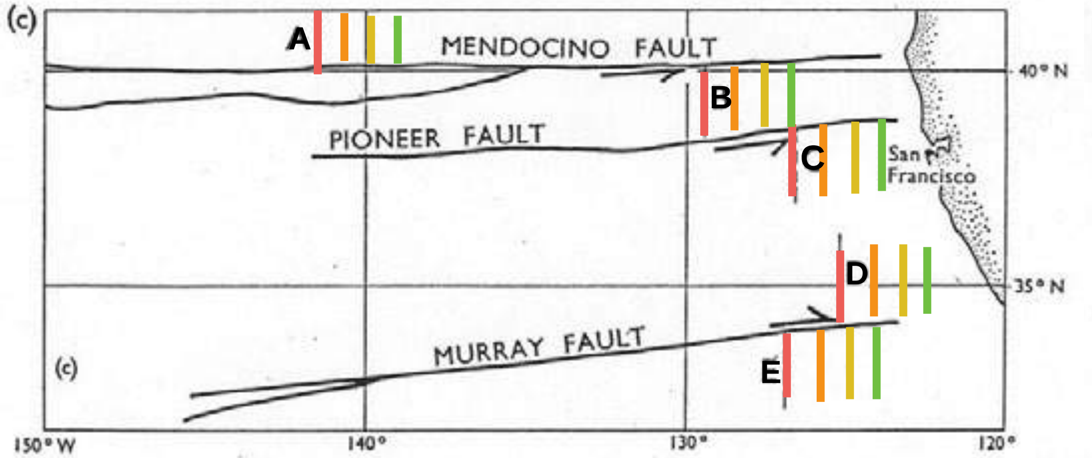
(a) Pattern of positive magnetic anomalies discovered in the Pacific floor off the coast between Seattle and San Francisco

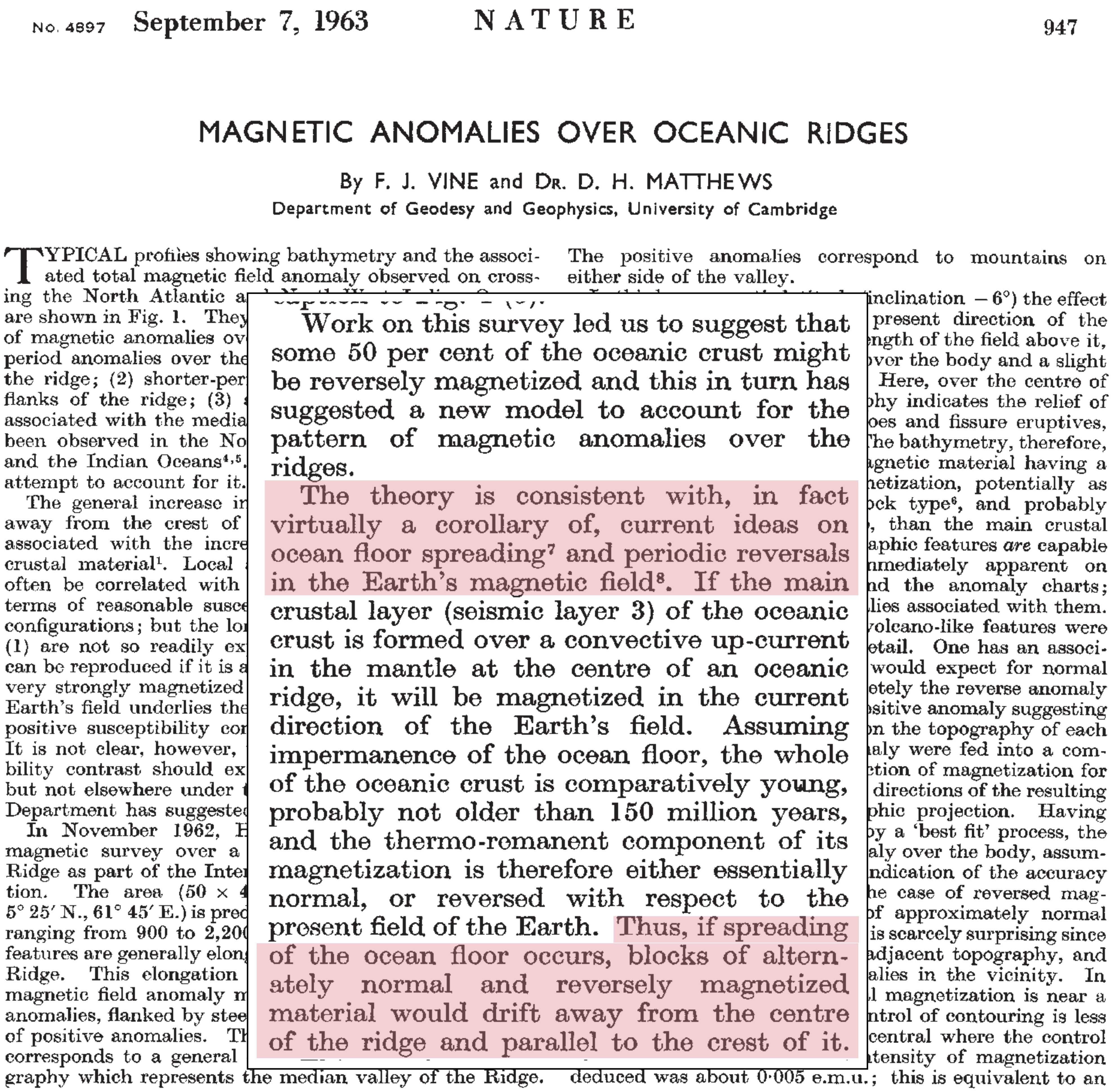
(b) Matching of profiles of magnetic anomalies from north and south of the Mendocino Fault, indicating a lateral displacement of 13° of longitude

(c) The magnetic anomalies on the north side of the Mendocino Fault can be matched with those on the south side only when two anomalies such as A and B, 1,160 km apart, are brought together. Similarly, the displacement along the Pioneer Fault is the distance between B and C, 265 km; and that along the Murray Fault the distance between D and E, 154 km. (*After A. D. Raff*, 1961)



Vacquier (1959) matches a magnetic anomaly pattern seen on the <u>north</u> side of the Mendocino Fracture Zone with an identical pattern on the <u>south</u> side – the two identical patterns are over 1000 km apart!





No. 4897 September 7, 1963 NATURE 947

MAGNETIC ANOMALIES OVER OCEANIC RIDGES

By F. J. VINE and Dr. D. H. MATTHEWS
Department of Geodesy and Geophysics, University of Cambridge

TYPICAL profiles showing bathymetry and the associated total magnetic field anomaly observed on crossing the North Atlantic a
are shown in Fig. 1. They
of magnetic anomalies ov
period anomalies over the
the ridge; (2) shorter-per
flanks of the ridge; (3)
associated with the media
been observed in the No
and the Indian Oceans[4,5].
attempt to account for it.
The general increase in
away from the crest of
associated with the incre
crustal material[1]. Local
often be correlated with
terms of reasonable susce
configurations; but the lo
(1) are not so readily ex
can be reproduced if it is a
very strongly magnetized
Earth's field underlies the
positive susceptibility con
It is not clear, however,
bility contrast should ex
but not elsewhere under
Department has suggeste
In November 1962, H
magnetic survey over a
Ridge as part of the Inter
tion. The area (50 × 4
5° 25′ N., 61° 45′ E.) is prec
ranging from 900 to 2,20
features are generally elon
Ridge. This elongation
magnetic field anomaly m
anomalies, flanked by stee
of positive anomalies. Th
corresponds to a general
graphy which represents the median valley of the Ridge.

The positive anomalies correspond to mountains on either side of the valley.
inclination −6°) the effect
present direction of the
ngth of the field above it,
ver the body and a slight
Here, over the centre of
hy indicates the relief of
oes and fissure eruptives,
he bathymetry, therefore,
gnetic material having a
etization, potentially as
ck type[6], and probably
, than the main crustal
aphic features *are* capable
mmediately apparent on
nd the anomaly charts;
lies associated with them.
olcano-like features were
etail. One has an associ-
would expect for normal
etely the reverse anomaly
sitive anomaly suggesting
n the topography of each
aly were fed into a com-
tion of magnetization for
directions of the resulting
phic projection. Having
y a 'best fit' process, the
aly over the body, assum-
ndication of the accuracy
he case of reversed mag-
f approximately normal
is scarcely surprising since
adjacent topography, and
alies in the vicinity. In
l magnetization is near a
ntrol of contouring is less
central where the control
tensity of magnetization
deduced was about 0·005 e.m.u.; this is equivalent to an

Work on this survey led us to suggest that some 50 per cent of the oceanic crust might be reversely magnetized and this in turn has suggested a new model to account for the pattern of magnetic anomalies over the ridges.

The theory is consistent with, in fact virtually a corollary of, current ideas on ocean floor spreading[7] and periodic reversals in the Earth's magnetic field[8]. If the main crustal layer (seismic layer 3) of the oceanic crust is formed over a convective up-current in the mantle at the centre of an oceanic ridge, it will be magnetized in the current direction of the Earth's field. Assuming impermanence of the ocean floor, the whole of the oceanic crust is comparatively young, probably not older than 150 million years, and the thermo-remanent component of its magnetization is therefore either essentially normal, or reversed with respect to the present field of the Earth. Thus, if spreading of the ocean floor occurs, blocks of alternately normal and reversely magnetized material would drift away from the centre of the ridge and parallel to the crest of it.

The very large bands of low gravity at the deep sea trenches was recognized as an important factor to be considered when thinking of how mountain belts are made.

Hess’s concept (1933) that the gravity lows of the trenches of Indonesia and West Indies are made by crustal down-buckles (which he called tectogenes)

A mechanical model – squeezing plastic layers to form a downbuckle, or ‘tectogene’ Kuenen, (1936).

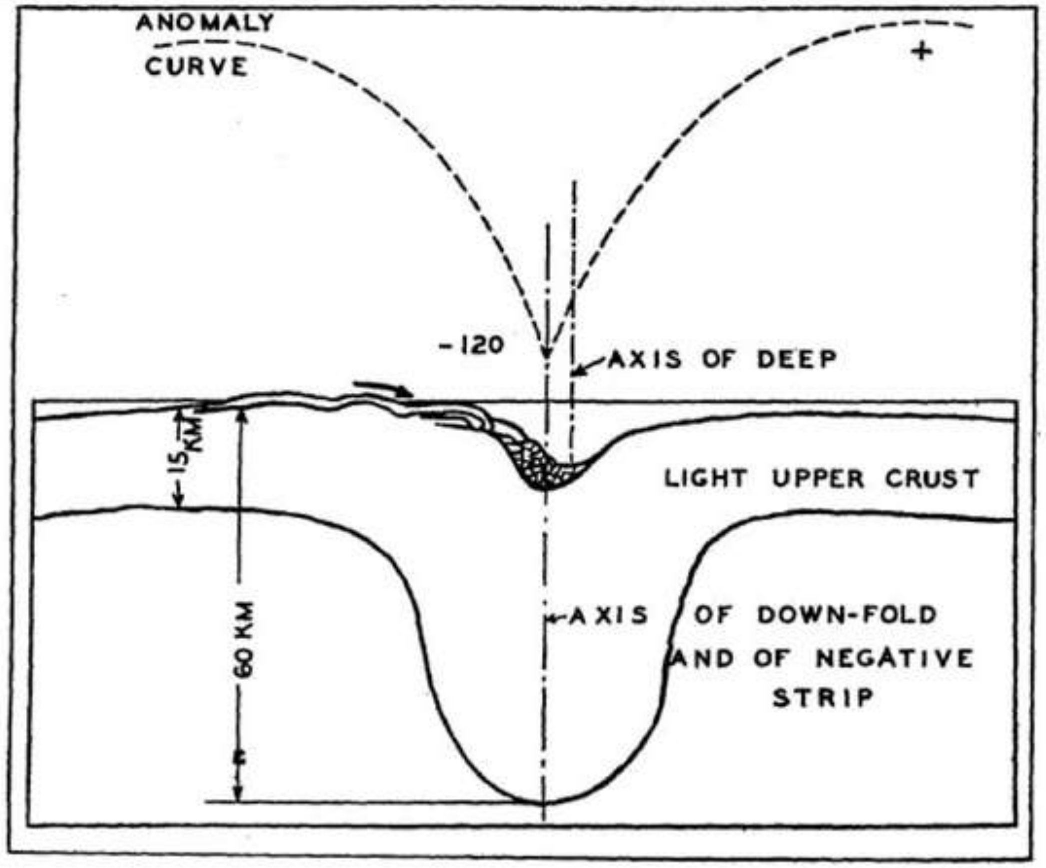


Figure 8.9. Harry Hess’s tectogene concept, 1933. Hess proposed that the linear belts of negative gravity anomalies associated with ocean deeps, in both the Caribbean and the Ea Indies, could be attributed to a down-buckling of the crust to form a low-density root. Sediments accumulating in the depression would eventually be deformed and uplifted, which would explain the transformation of geosynclines into mountain belts. The dashed line at the top of the diagram represents an idealized gravity profile over the down-buckled crust. (Field 1933, p. 30.)

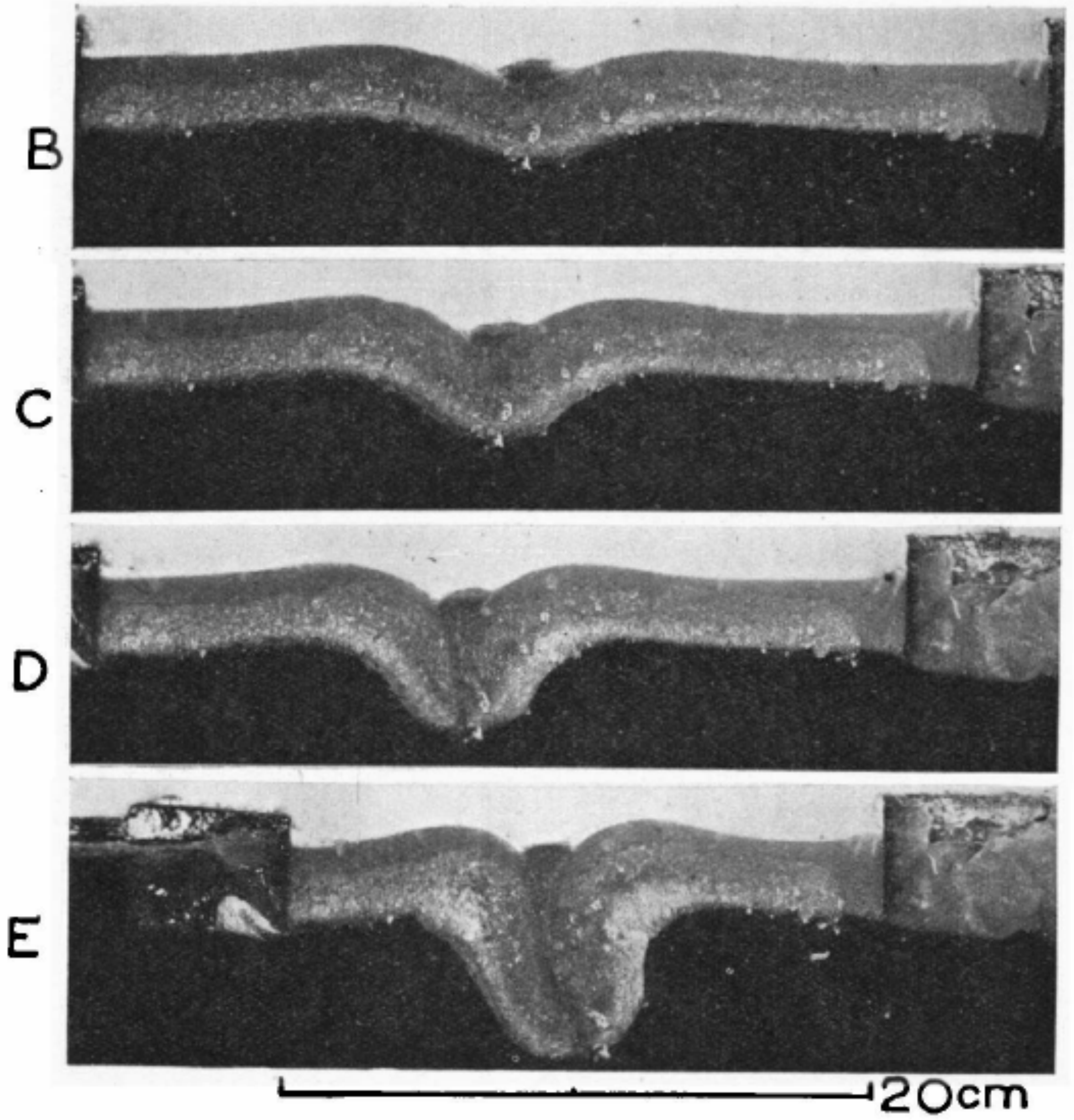
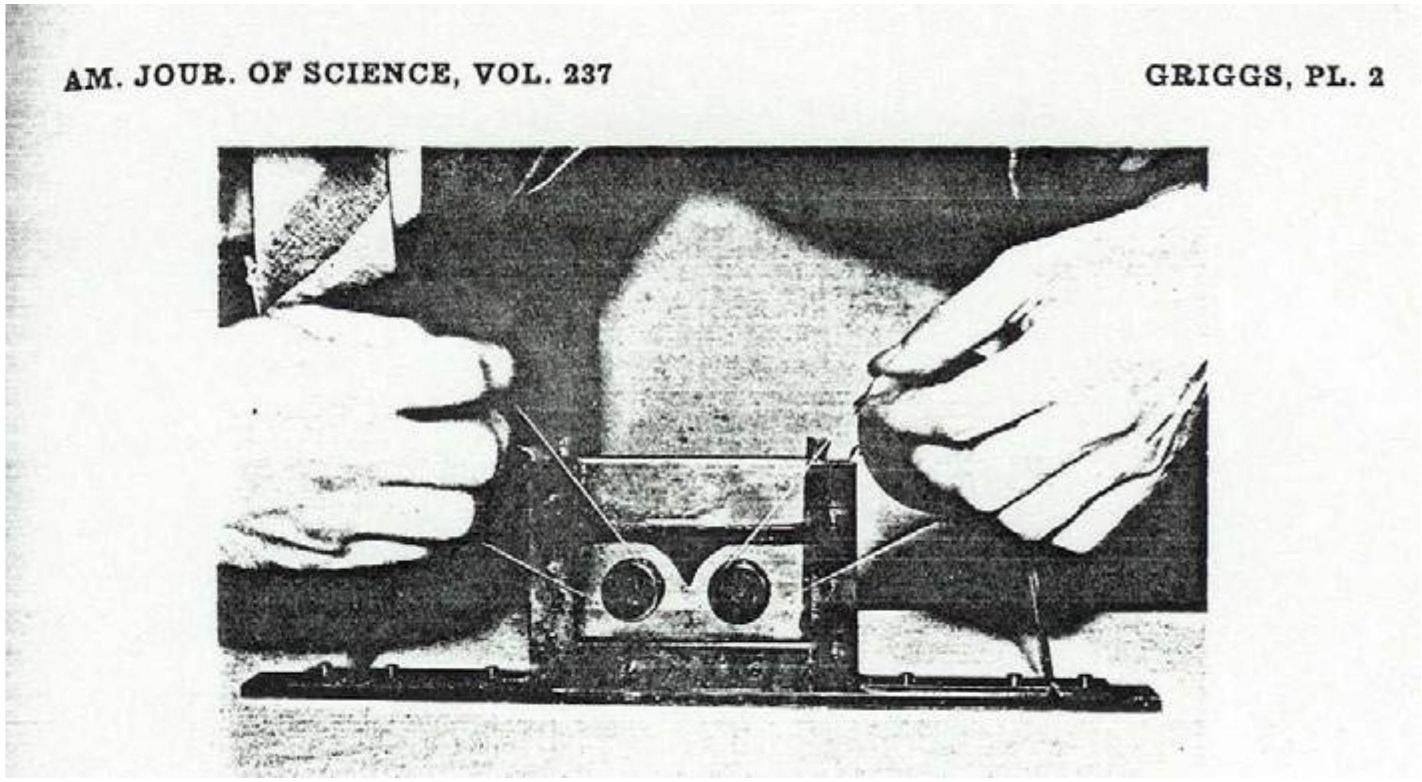
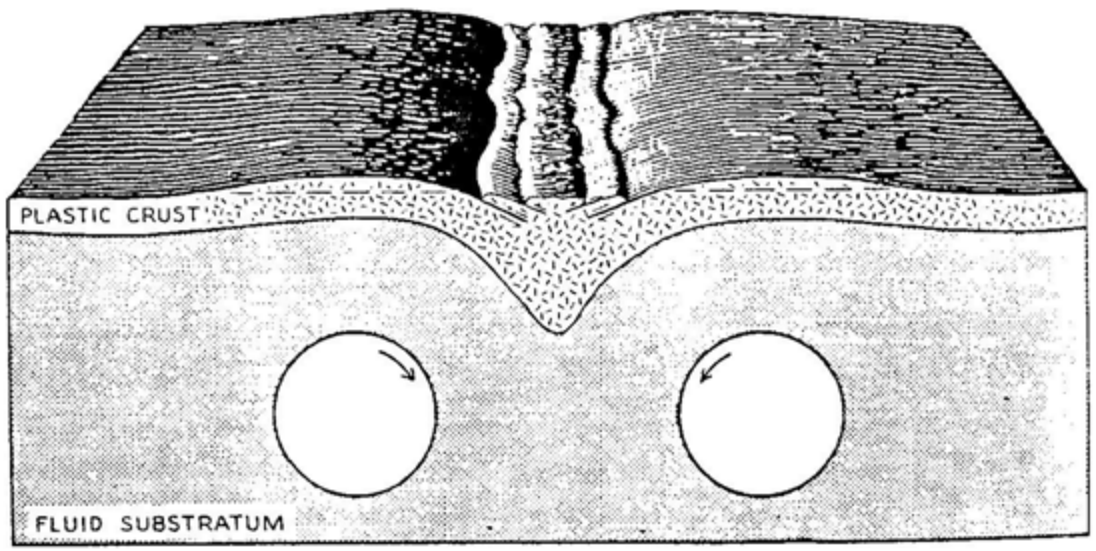


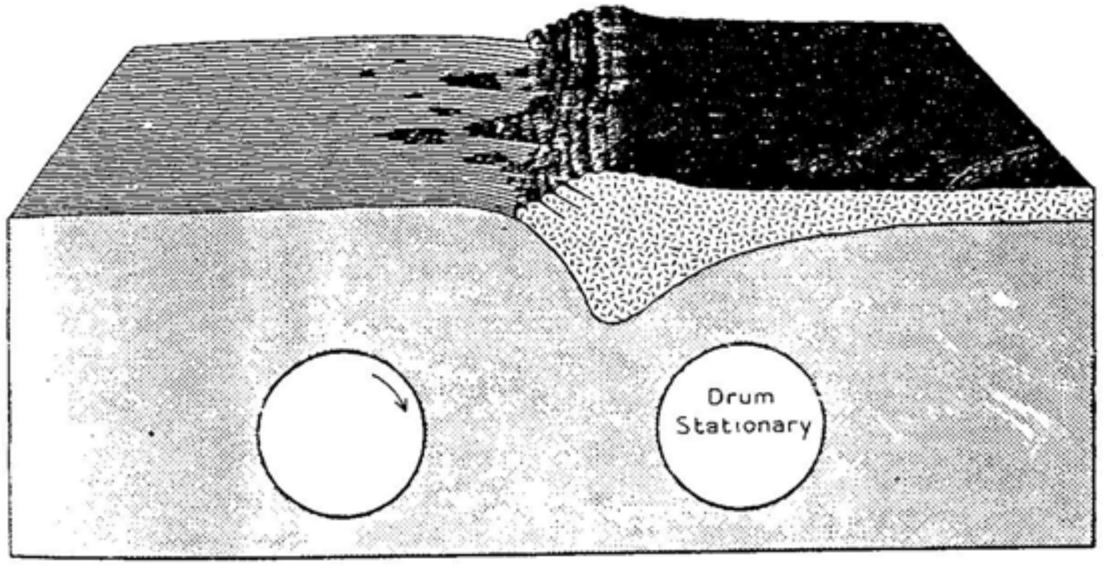
Fig. 7.

Experiments IIA. Successive stages in the growth of a synclinal fold in a highly plastic crust, that was slightly bent into a geosyncline by a strip of soft materials. Stage B after slight compression. Compare the relatively small depth of the topographic depression with that forming when the crust has more strength (fig. 5).

Here David Griggs (UCLA, 1938) made a simple apparatus to study mountain building. He could not model convection currents, but approximated their effects with the drag induced by hand-cranked rollers.







Symmetric convergence produces a downbuckle (named ‘tectogene’) then popular in models.

One-sided convergence produces a deep-sea trench/island-arc pattern.

H. W. Menard, Marine Geology of the Pacific, McGraw-Hill, 217 pp., 1964.

1- Introduction
2- Normal Basin
3- Great Faults
4- Vulcanism
5- Trenches and Island Arcs
6- Oceanic Ridges
7- Pelagic Sediments
8- Manganese Nodules
9- Turbidity Currents
10- Continental Margins
11- Geological History

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Crustal structure of the mid−ocean ridges: 1. Seismic refraction measurements, X. Le Pichon, R.E. Houtz, C.L. Drake, and J.E. Nafe, *J. Geophys. Res.*, 1965.

Crustal structure of the mid−ocean ridges: 2. Computed model from gravity and seismic refraction data, M. Talwani, X. Le Pichon, and M. Ewing, *J. Geophys. Res.*, 1965.

Crustal structure of the mid−ocean ridges: 3. Magnetic anomalies over the mid−Atlantic ridge, J. R. Heirtzler, and X. Le Pichon, *J. Geophys. Res.*, 1965.

Crustal structure of the mid−ocean ridges: 4. Sediment distribution in the South Atlantic Ocean and the Cenozoic history of the Mid−Atlantic Ridge, M. Ewing, X. Le Pichon, and J. Ewing, *J. Geophys. Res.*, 1966.

Crustal structure of the mid−ocean ridges: 5. Heat flow through the Atlantic Ocean floor and convection currents, M.G. Langseth and X. Le Pichon, *J. Geophys. Res.*, 1966.

JOURNAL OF GEOPHYSICAL RESEARCH VOL. 70, NO. 24 DECEMBER 15, 1965

Gravity Anomalies and Convection Currents

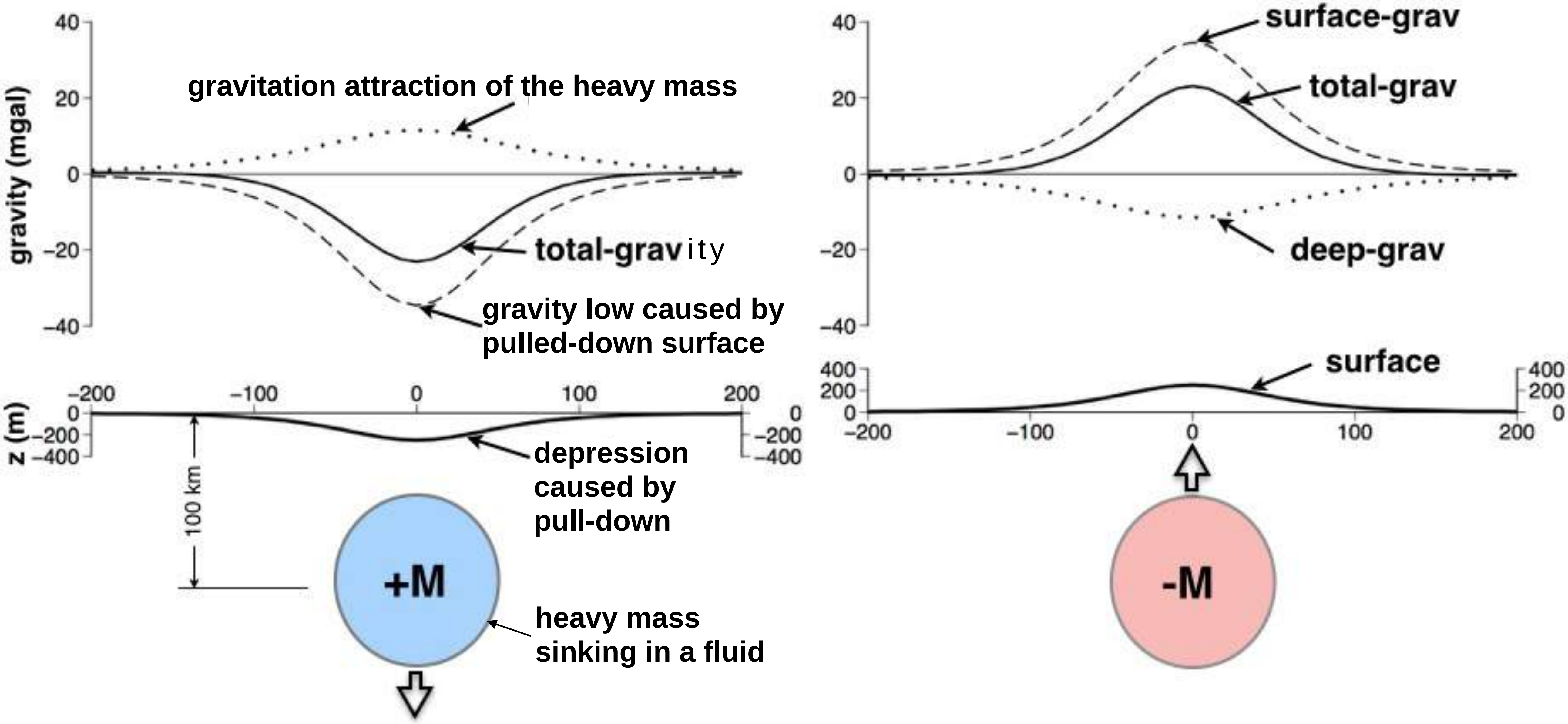
1. A Sphere and Cylinder Sinking beneath the Surface of a Viscous Fluid

W. JASON MORGAN

Princeton University, Princeton, New Jersey

Abstract. The effects of a sphere and a cylinder sinking beneath the surface of a viscous fluid are examined, and two results are found: (1) the horizontal divergence of the velocity at the surface of the fluid is related to the measured free-air anomaly if the viscosity of the fluid is uniform, and (2) the vertical load supported at the surface is essentially independent of any vertical variation of the viscosity of the fluid. The vertical load supported at the surface, F_{zz}, or the magnitude of the depression if the surface is a free surface, is found by an image solution. The solution formally has a pressure term and a velocity term. If the viscosity is constant, we find through an identity of integrals that the contribution to the surface load represented by the pressure term exactly cancels the gravitational attraction of the density inhomogeneities beneath the surface for any arbitrary density distribution. The net attracting mass, which produces the net free-air anomaly, is then related only to the velocity divergence. This theorem is limited in its application because it is sensitive to viscosity variations with depth. It is found that F_{zz} is independent of the viscosity of the fluid and also of the boundary conditions of the top surface—a free surface or a rigid plate give the same F_{zz}. A two-layer model in which a fluid of one viscosity lies over a fluid of another viscosity is examined, and it is found that F_{zz} is relatively independent of the thickness of the top layer or the ratio of the two viscosities, especially if the top layer has the greater viscosity. Whereas the horizontal velocity at the surface is very dependent upon the assumed viscosity pattern, the vertical load F_{zz} is not, and this enables us to find the approximate mass of a sinking body and its depth beneath the surface independently of the viscosity pattern of the earth.

A sphere sinking/rising in a uniform viscosity mantle, showing the resulting surface depression/bump and the resulting gravity anomaly


gravitation attraction of the heavy mass

total-gravity

gravity low caused by pulled-down surface

depression caused by pull-down

heavy mass sinking in a fluid

surface-grav

total-grav

deep-grav

surface

Sphere r = 50 km $\Delta\rho = 1\%$ ($\Delta T \approx 300°C$)

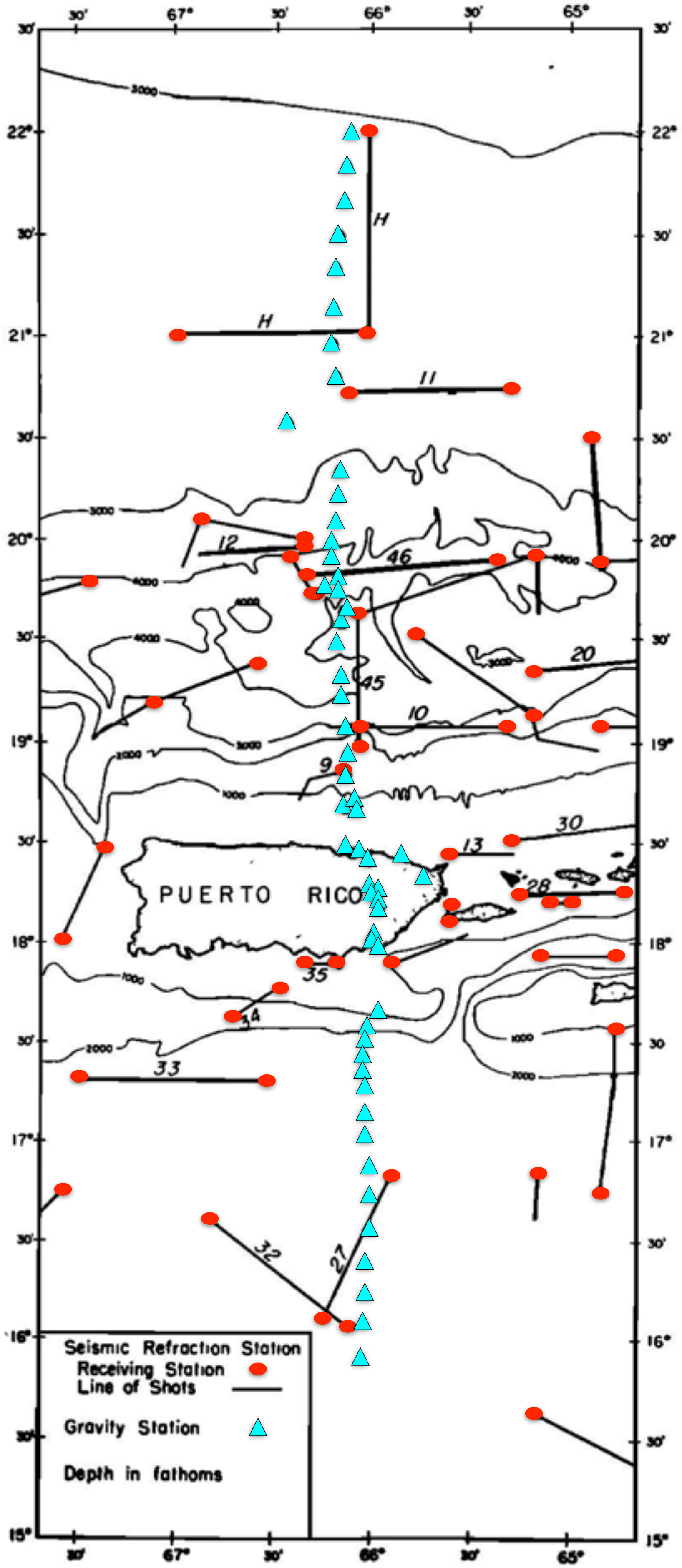


FIG. 1—Location of seismic refraction and gravity stations.

1550 TALWANI, SUTTON, AND WORZEL *(JGR, 1959)*

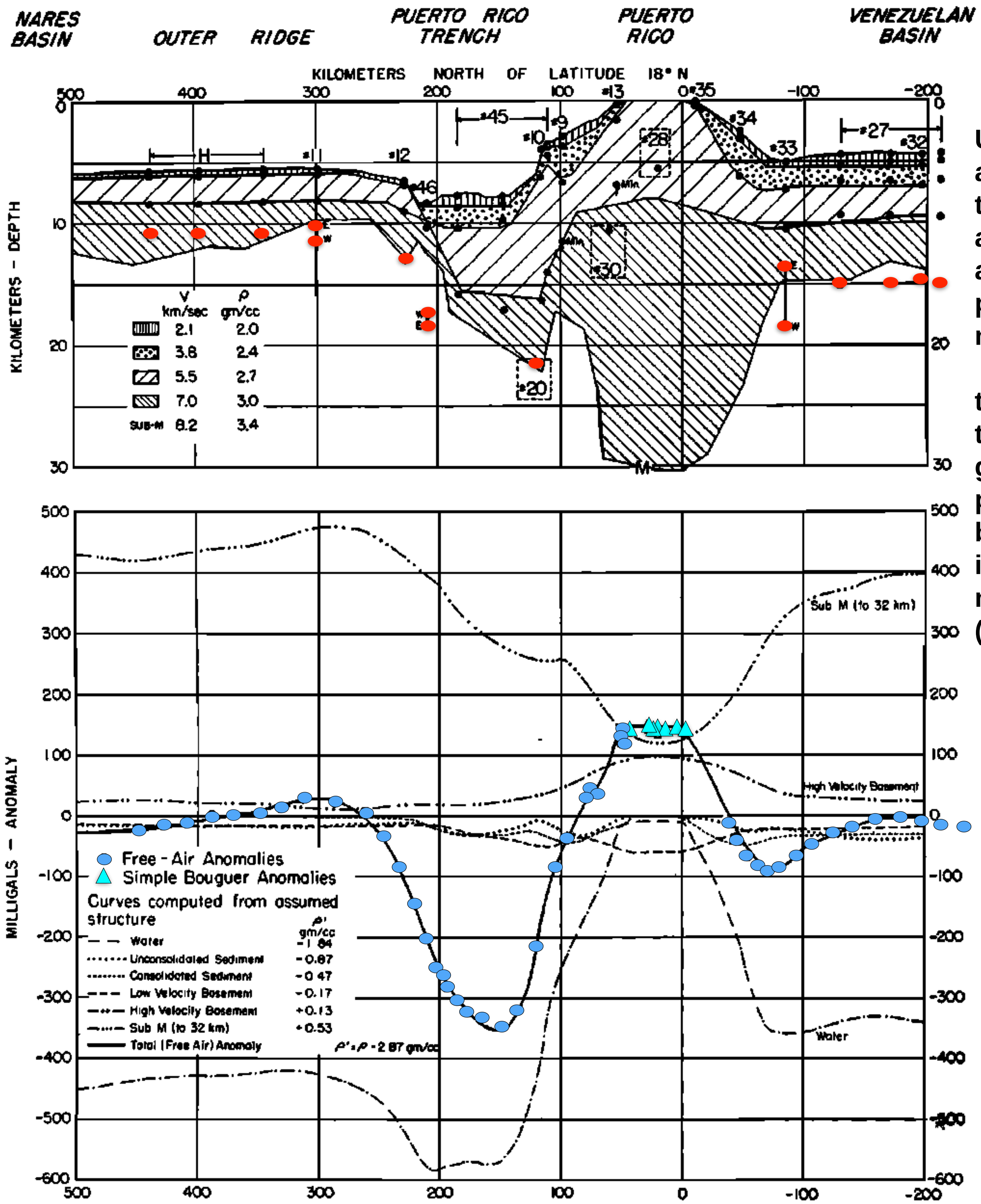


FIG. 3—*Upper*—Computed crustal section. Crustal layering is from seismic data; M is from gravity data; points are seismic interfaces. *Lower*—Computed attraction of layers to 32-km depth using reduced densities ρ'. Solid curve is total attraction (computed free-air anomaly) which is compared with observed anomalies.

Using thickness and density of the upper layers as shown, then adjusting trial positions of the moho (black line),

they then compute the expected gravity along this profile (black line below) and compare it to the gravity measurements (blue dots)

data collected:

29 submarine dives (grav)

9 land gravity stations

35 2-ship refraction lines

I took the view that the gravity here was the pattern you would expect to get from a typical isostatic island plus the pull-down effect of a heavy sinking body (*i.e.*, convection).

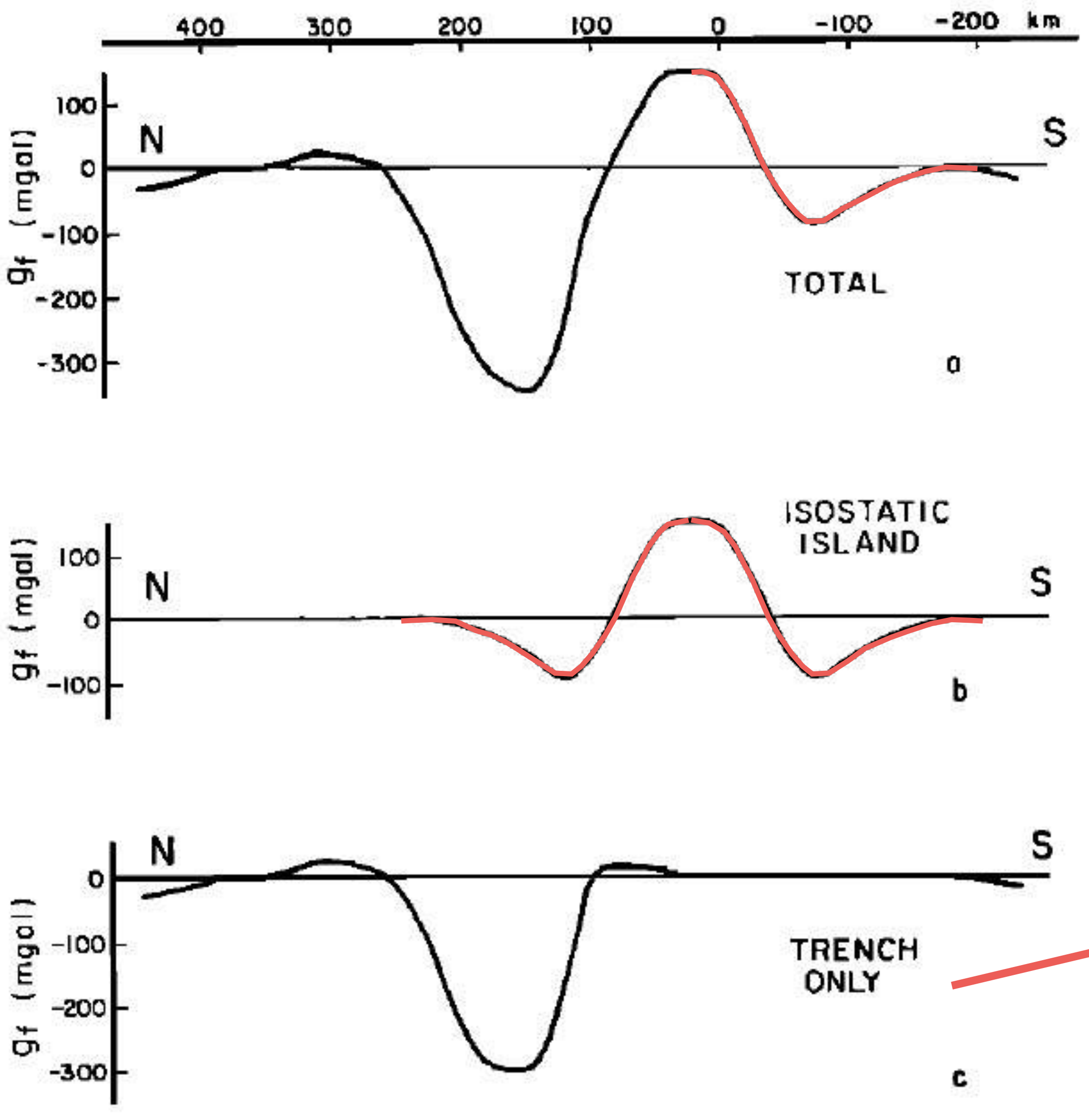


Fig. 3. The free-air anomaly of Puerto Rico decomposed into two parts: a symmetrical 'isostatic island' and the remaining 'trench only.'

Fit the 'trench only' part with gravity computed with the cylinder sinker model:

depth = 80 km Mass = 1.7 x 10^{18} g/cm

depth = 100 km Mass = 2.2 x 10^{19} g/cm

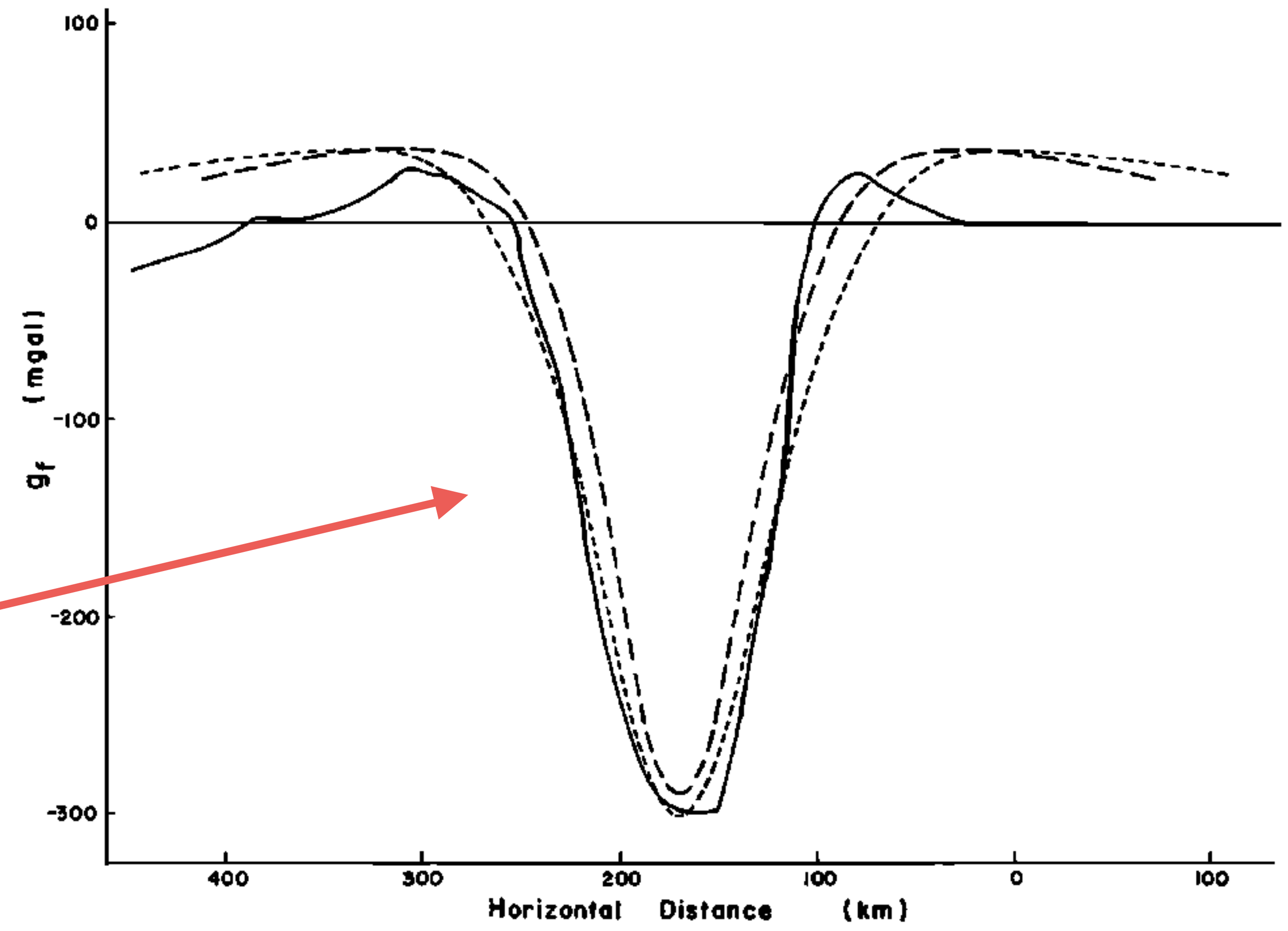
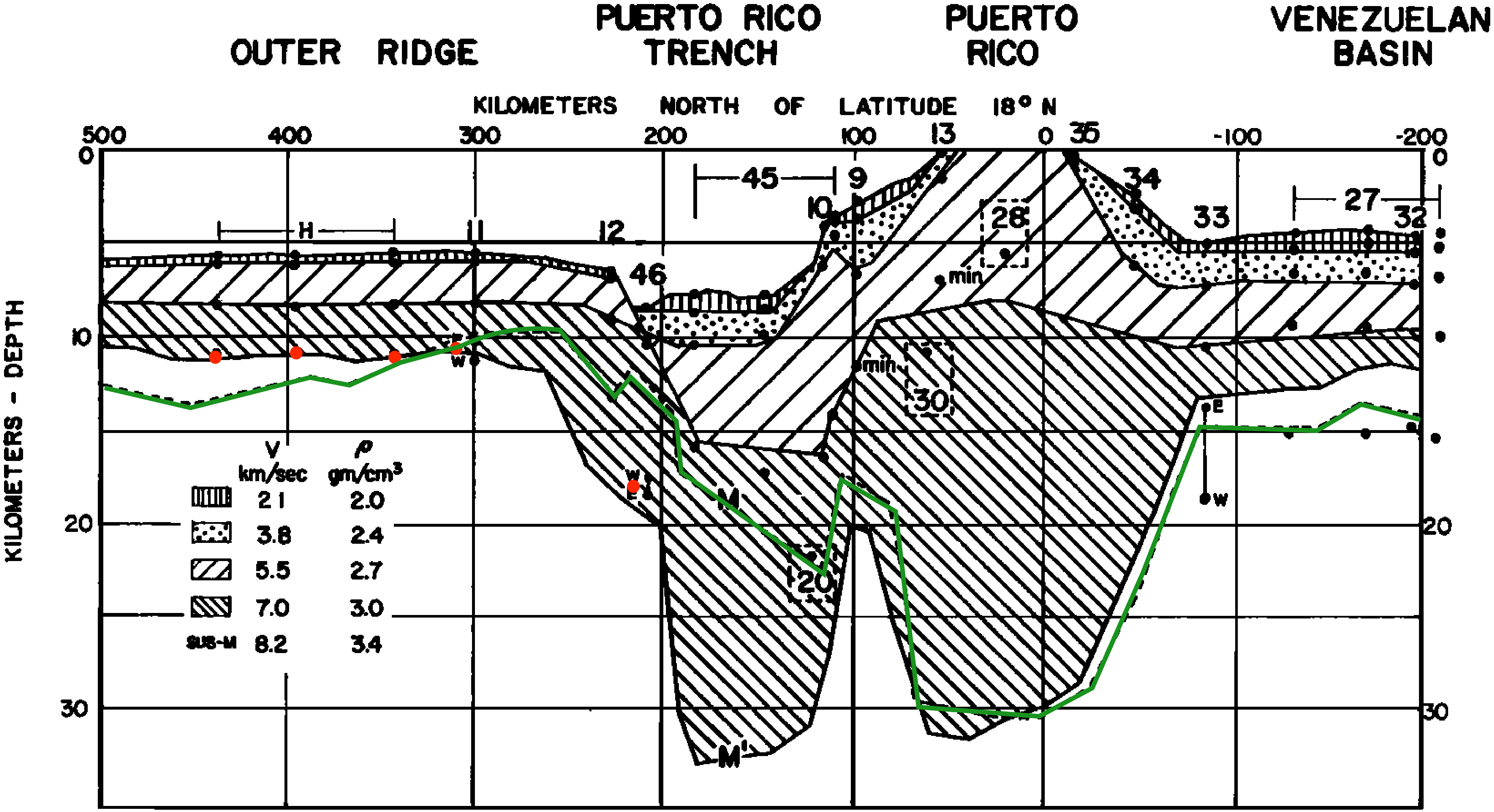
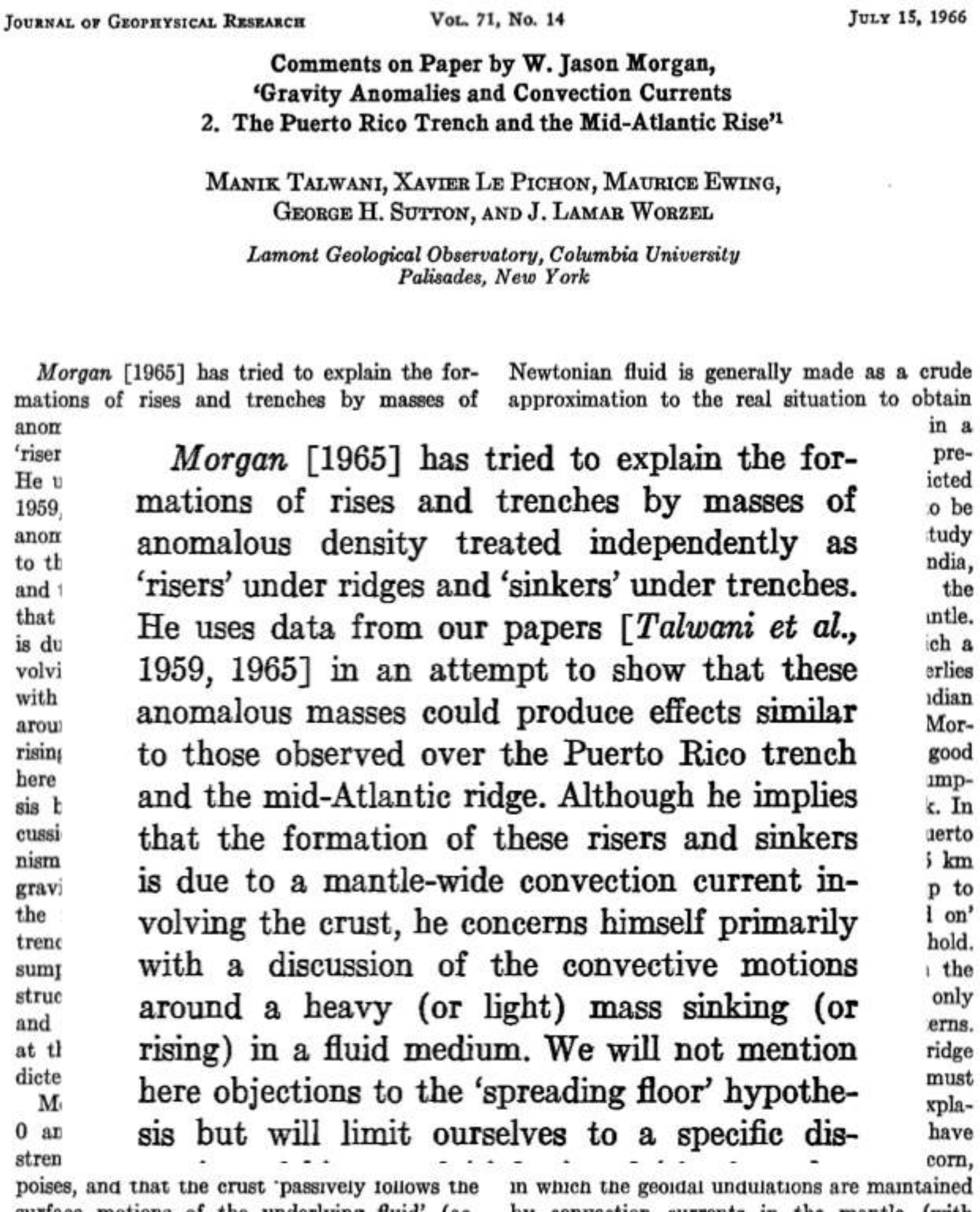


Fig. 4. The free-air anomaly of the residual 'trench only' and two choices of parameters of the simple viscous model. *Solid line,* Puerto Rico 'trench only'; *long dashes,* fit with $D = 80$ km, $M_L = 1.7 \times 10^{18}$ g/cm; *short dashes,* fit with $D = 100$ km, $M_L = 2.2 \times 10^{18}$ g/cm.

Adjust the Moho depth to fit the measured gravity profile with a ‘sinker’ 100 km beneath the trench.



(a)



Journal of Geophysical Research Vol. 71, No. 14 July 15, 1966

Comments on Paper by W. Jason Morgan, 'Gravity Anomalies and Convection Currents 2. The Puerto Rico Trench and the Mid-Atlantic Rise'[1]

Manik Talwani, Xavier Le Pichon, Maurice Ewing,
George H. Sutton, and J. Lamar Worzel

Lamont Geological Observatory, Columbia University
Palisades, New York

Morgan [1965] has tried to explain the formations of rises and trenches by masses of anomalous density treated independently as 'risers' under ridges and 'sinkers' under trenches. He uses data from our papers [*Talwani et al.*, 1959, 1965] in an attempt to show that these anomalous masses could produce effects similar to those observed over the Puerto Rico trench and the mid-Atlantic ridge. Although he implies that the formation of these risers and sinkers is due to a mantle-wide convection current involving the crust, he concerns himself primarily with a discussion of the convective motions around a heavy (or light) mass sinking (or rising) in a fluid medium. We will not mention here objections to the 'spreading floor' hypothesis but will limit ourselves to a specific dis-

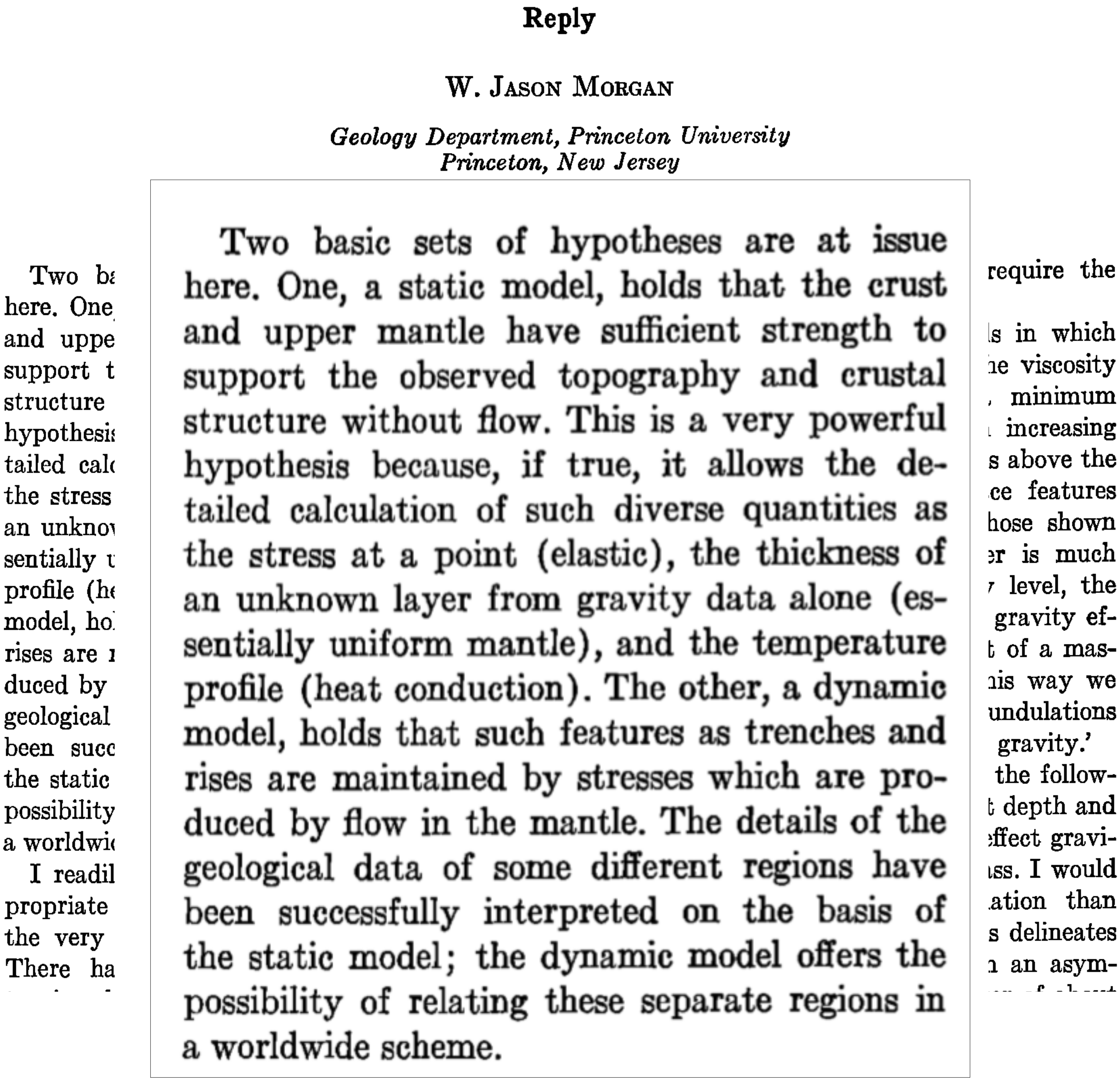
poises, and that the crust 'passively follows the

Newtonian fluid is generally made as a crude approximation to the real situation to obtain

in which the geoidal undulations are maintained

In their 5-page comment, they made either 43 or 47 (I forget the exact number) specific objections to my 1965 paper.

In my reply, I didn't address their 43(?) points, instead stating this was a difference in viewpoint of how the earth worked – mobilist vs. fixist.



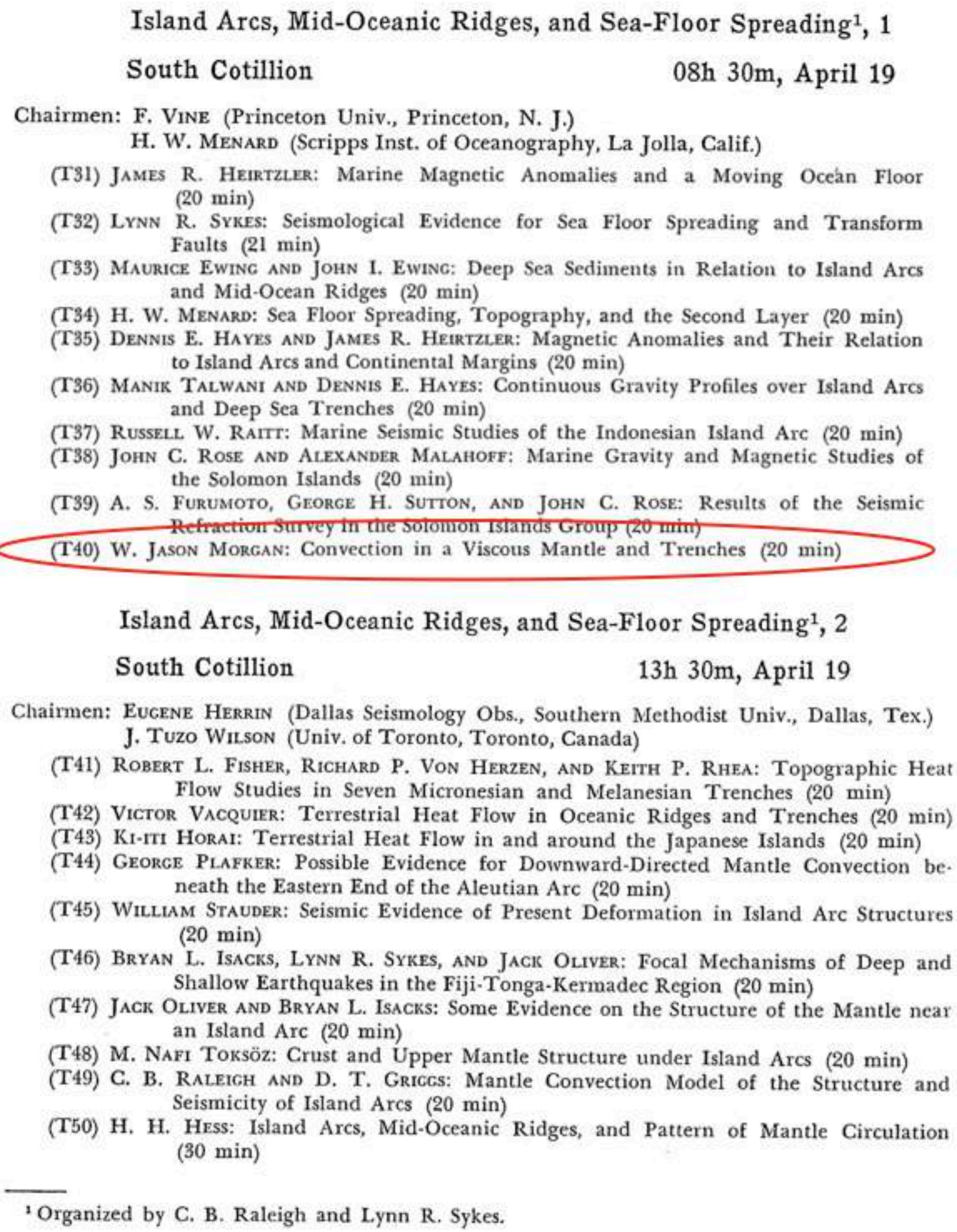
Reply

W. JASON MORGAN

Geology Department, Princeton University
Princeton, New Jersey

Two basic sets of hypotheses are at issue here. One, a static model, holds that the crust and upper mantle have sufficient strength to support the observed topography and crustal structure without flow. This is a very powerful hypothesis because, if true, it allows the detailed calculation of such diverse quantities as the stress at a point (elastic), the thickness of an unknown layer from gravity data alone (essentially uniform mantle), and the temperature profile (heat conduction). The other, a dynamic model, holds that such features as trenches and rises are maintained by stresses which are produced by flow in the mantle. The details of the geological data of some different regions have been successfully interpreted on the basis of the static model; the dynamic model offers the possibility of relating these separate regions in a worldwide scheme.

American Geophysical Union
Spring Meeting
Washington, D.C.
March 1967



Island Arcs, Mid-Oceanic Ridges, and Sea-Floor Spreading[1], 1

South Cotillion — 08h 30m, April 19

Chairmen: F. VINE (Princeton Univ., Princeton, N. J.)
H. W. MENARD (Scripps Inst. of Oceanography, La Jolla, Calif.)

(T31) JAMES R. HEIRTZLER: Marine Magnetic Anomalies and a Moving Ocean Floor (20 min)
(T32) LYNN R. SYKES: Seismological Evidence for Sea Floor Spreading and Transform Faults (21 min)
(T33) MAURICE EWING AND JOHN I. EWING: Deep Sea Sediments in Relation to Island Arcs and Mid-Ocean Ridges (20 min)
(T34) H. W. MENARD: Sea Floor Spreading, Topography, and the Second Layer (20 min)
(T35) DENNIS E. HAYES AND JAMES R. HEIRTZLER: Magnetic Anomalies and Their Relation to Island Arcs and Continental Margins (20 min)
(T36) MANIK TALWANI AND DENNIS E. HAYES: Continuous Gravity Profiles over Island Arcs and Deep Sea Trenches (20 min)
(T37) RUSSELL W. RAITT: Marine Seismic Studies of the Indonesian Island Arc (20 min)
(T38) JOHN C. ROSE AND ALEXANDER MALAHOFF: Marine Gravity and Magnetic Studies of the Solomon Islands (20 min)
(T39) A. S. FURUMOTO, GEORGE H. SUTTON, AND JOHN C. ROSE: Results of the Seismic Refraction Survey in the Solomon Islands Group (20 min)
(T40) W. JASON MORGAN: Convection in a Viscous Mantle and Trenches (20 min)

Island Arcs, Mid-Oceanic Ridges, and Sea-Floor Spreading[1], 2

South Cotillion — 13h 30m, April 19

Chairmen: EUGENE HERRIN (Dallas Seismology Obs., Southern Methodist Univ., Dallas, Tex.)
J. TUZO WILSON (Univ. of Toronto, Toronto, Canada)

(T41) ROBERT L. FISHER, RICHARD P. VON HERZEN, AND KEITH P. RHEA: Topographic Heat Flow Studies in Seven Micronesian and Melanesian Trenches (20 min)
(T42) VICTOR VACQUIER: Terrestrial Heat Flow in Oceanic Ridges and Trenches (20 min)
(T43) KI-ITI HORAI: Terrestrial Heat Flow in and around the Japanese Islands (20 min)
(T44) GEORGE PLAFKER: Possible Evidence for Downward-Directed Mantle Convection beneath the Eastern End of the Aleutian Arc (20 min)
(T45) WILLIAM STAUDER: Seismic Evidence of Present Deformation in Island Arc Structures (20 min)
(T46) BRYAN L. ISACKS, LYNN R. SYKES, AND JACK OLIVER: Focal Mechanisms of Deep and Shallow Earthquakes in the Fiji-Tonga-Kermadec Region (20 min)
(T47) JACK OLIVER AND BRYAN L. ISACKS: Some Evidence on the Structure of the Mantle near an Island Arc (20 min)
(T48) M. NAFI TOKSÖZ: Crust and Upper Mantle Structure under Island Arcs (20 min)
(T49) C. B. RALEIGH AND D. T. GRIGGS: Mantle Convection Model of the Structure and Seismicity of Island Arcs (20 min)
(T50) H. H. HESS: Island Arcs, Mid-Oceanic Ridges, and Pattern of Mantle Circulation (30 min)

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[1] Organized by C. B. Raleigh and Lynn R. Sykes.

In January, 1967, Bill Menard (Scripps) published a short paper in Science. In earlier papers and in his book on ‘Marine Geology of the Pacific’, he had stated that the great fracture zones of the Pacific followed great-circle paths.

To show they are not great circles, he plots the great fracture zones on a ‘gnomonic projection’. (On a ‘gnomonic projection’ [also called a ‘great circle projection’], any straight line is a great circle.)

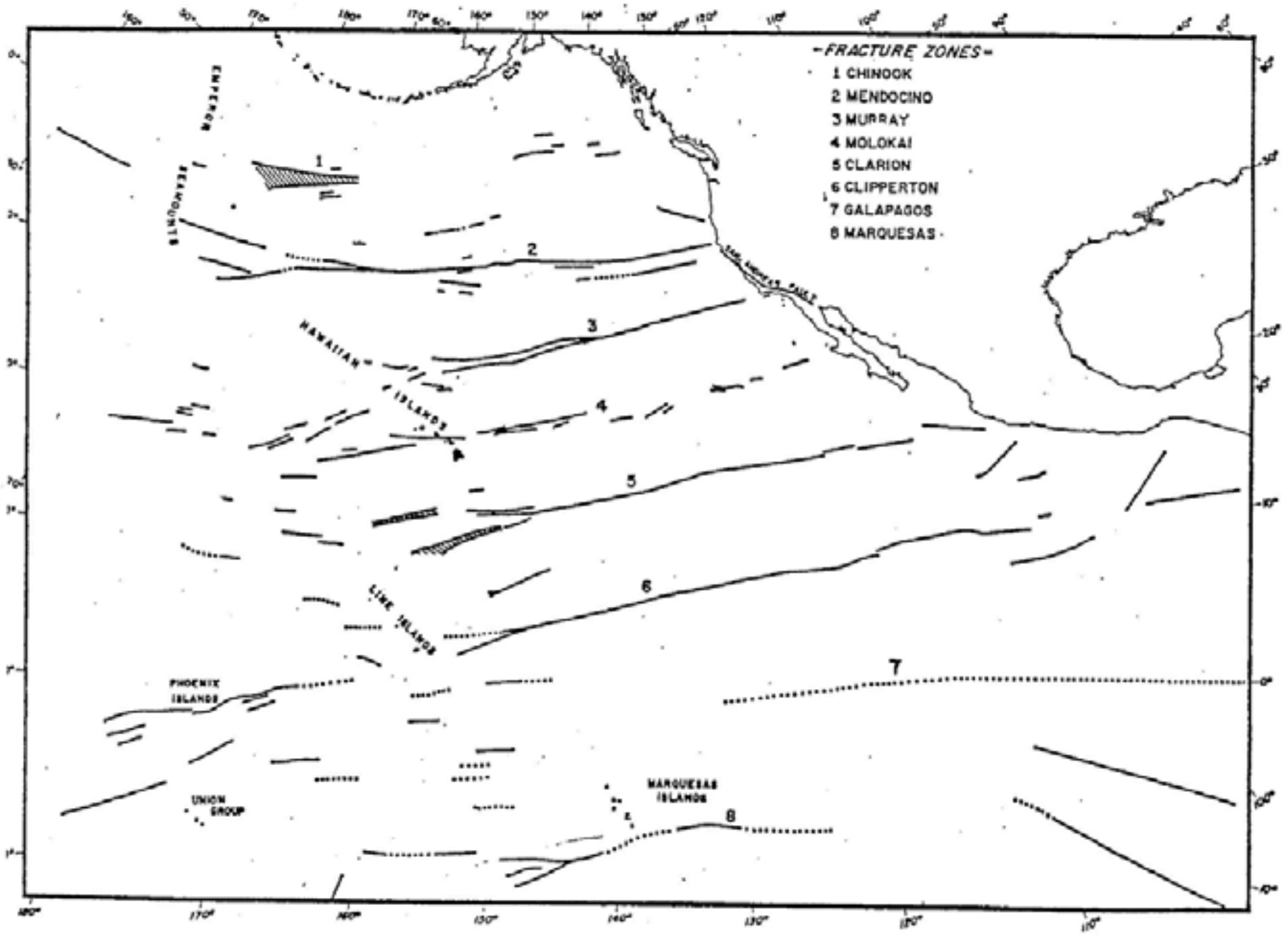
I saw this figure and instantly saw the great fracture zones were probably concentric circles about a common pole,

g. 1. Principal fracture zones of the northeastern and central Pacific; equal-area ojection. Stippling indicates smooth archipelagic aprons and the belt of equatorial lagic smoothing; white areas within archipelagic aprons are volcanoes and volcanic dges. Individual lineations are troughs, asymmetric ridges, or regional changes in pth; broken-line bands have fracture-zone topography, but information is not lequate for the tracing of individual lineations.

along a great circle is 9900 km, or about a quarter of the circumference of Earth (Fig. 2).

Many other great fracture zones have been traced for 4000 to 6000 km (Fig. 1) but do not follow great circles over such distances. The most notable exception from a great-circle trend is the Mendocino fracture zone, which changes trend from west to southwest to west and follows the general trend of the other northeastern Pacific zones only in its central portion.

Like the Clipperton zone, the other fracture zones change from predominantly simple lineations in the northeastern Pacific to branching features, with common west and southwest trends, in the central Pacific. The edge of the East Pacific Rise can be defined by the western margin of the sloping flank. Branching occurs west of this margin but at a rather constant distance. On the other hand, if the "ICSU Line," proposed by Wilson (*6*) on the basis of tectonic arguments to be the edge of the rise, is accepted, the branching occurs on the rise; how-



g. 2. Principal fracture zones of the northeastern and central Pacific; great-circle projection. A straight line on this projection part of a true great circle.

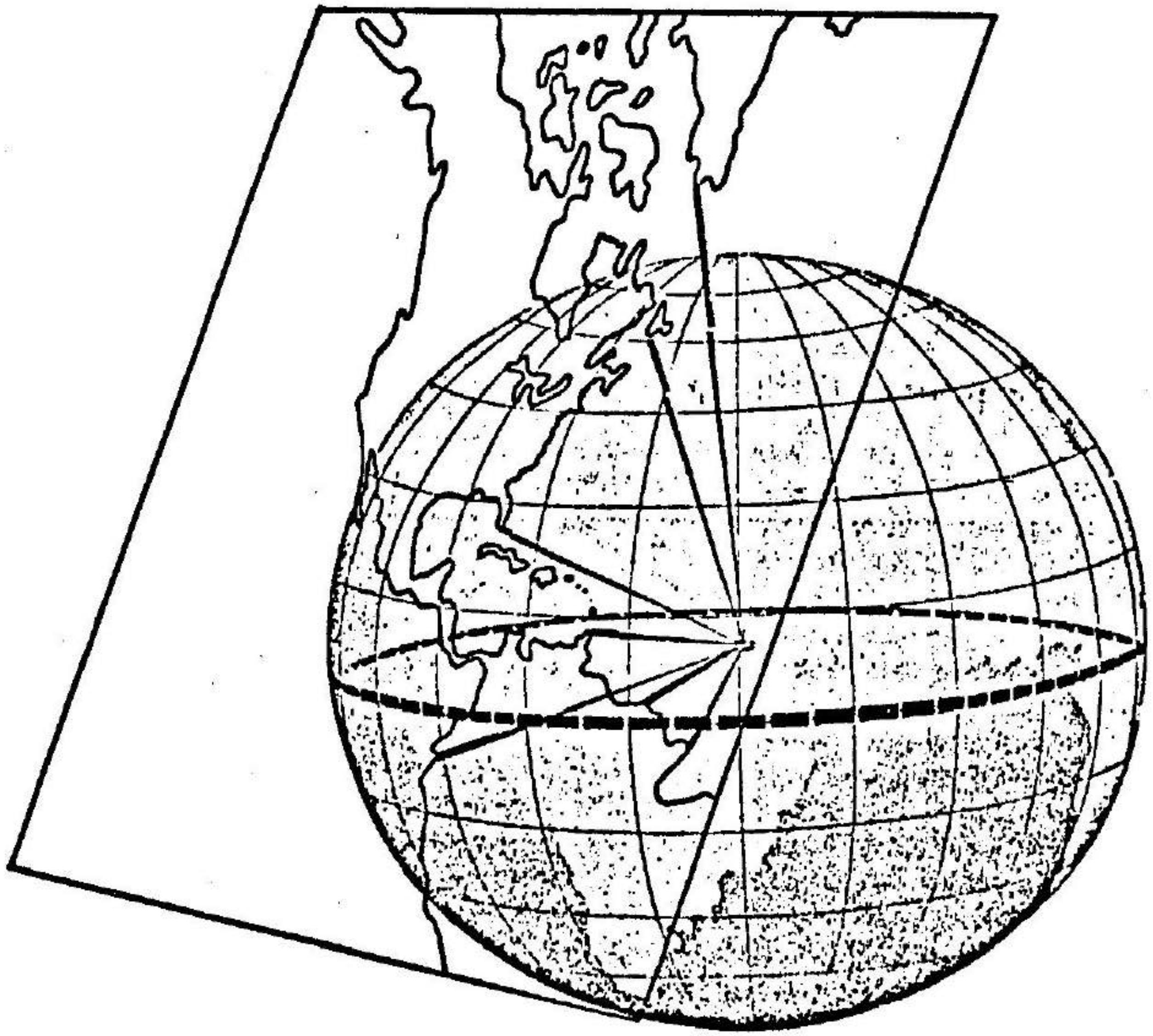


FIGURE 317a.—An oblique gnomonic projection.

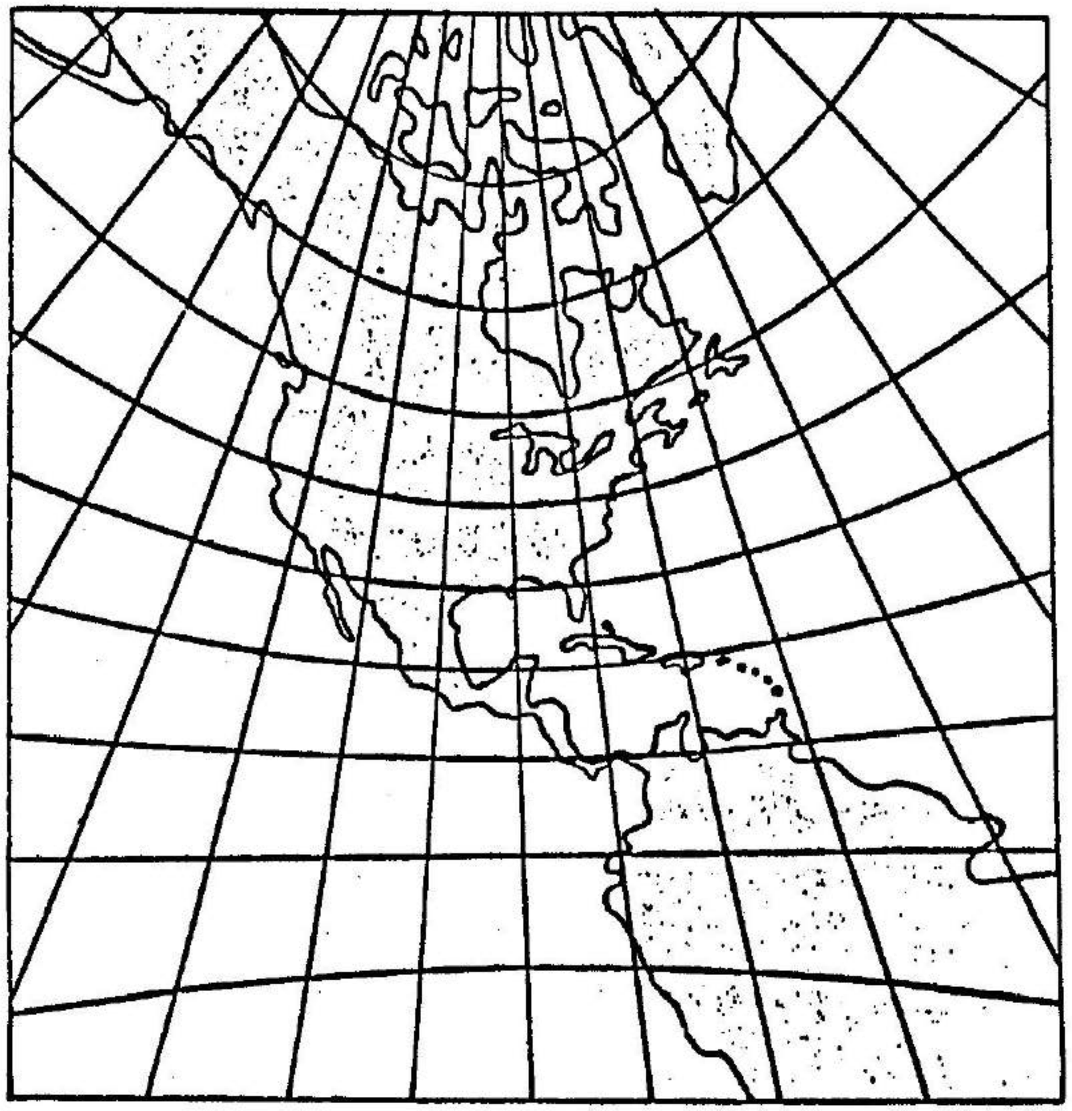


FIGURE 317b.—A gnomonic map with point of tangency at latitude 30° N, longitude 90° W.

Figures on the gnomonic projection in 'Bowditch' (The American Practical Navigator)

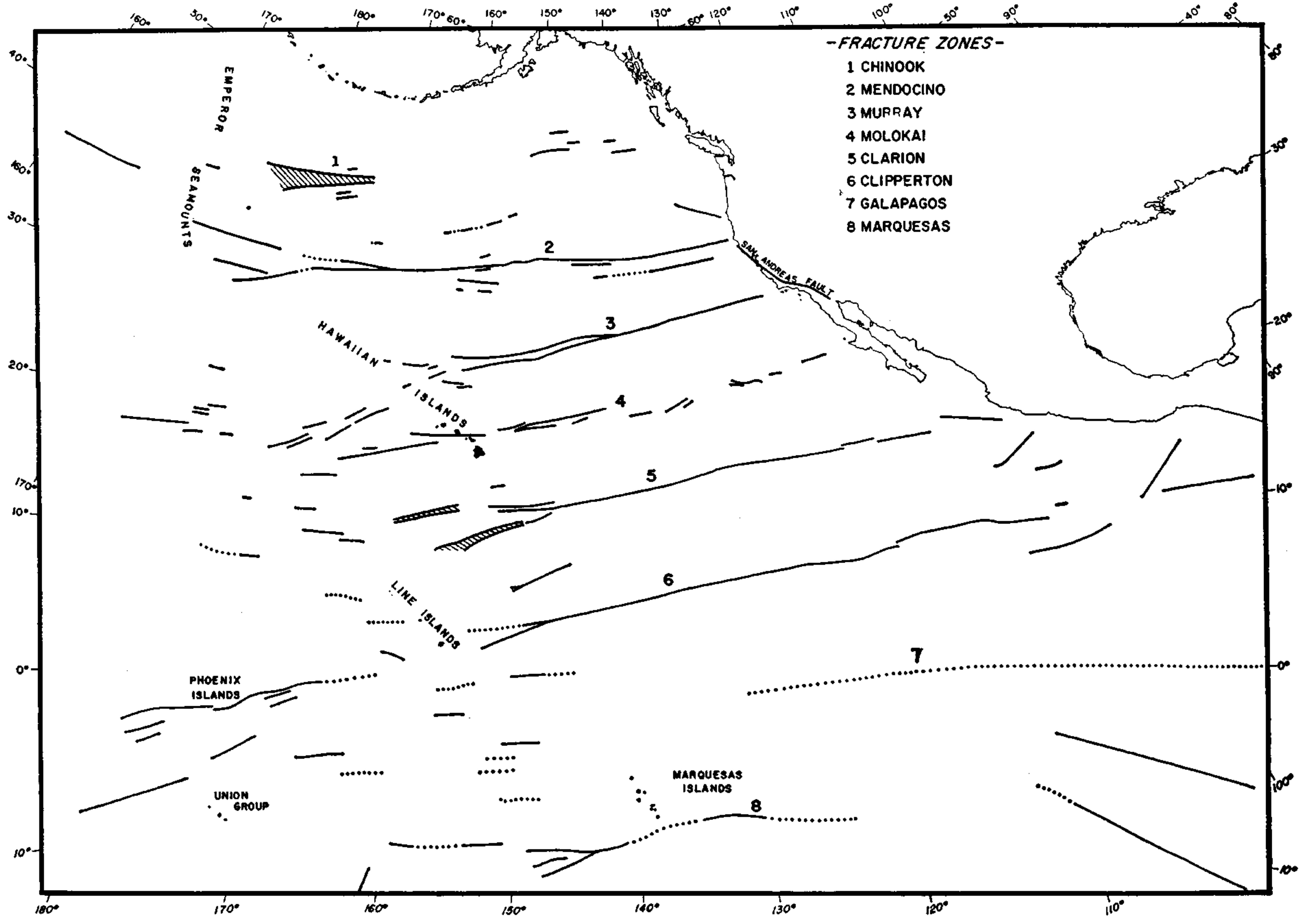


Fig. 2. Principal fracture zones of the northeastern and central Pacific; great-circle projection. A straight line on this projection is part of a true great circle.

(Menard, Jan 6, 1967 – gnomonic map of fracture zones)

Test: Can I find one pole that all these fracture zones are concentric about?

Pole at 78.85 N 111.46 E

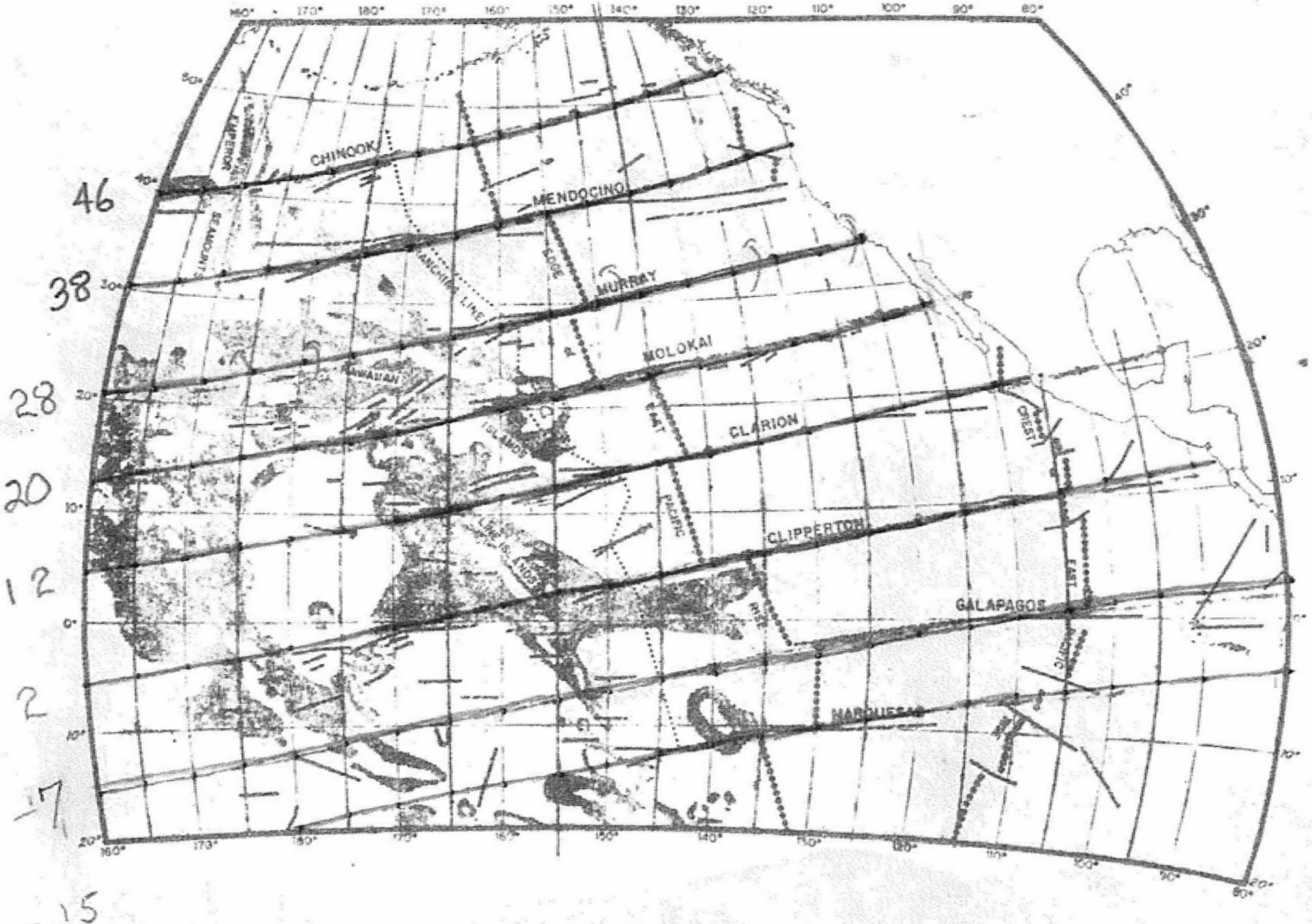


Fig. 1. Principal fracture zones of the northeastern and central Pacific; equal-area projection. Stippling indicates smooth archipelagic aprons and the belt of equatorial pelagic smoothing; white areas within archipelagic aprons are volcanoes and volcanic ridges. Individual lineations are troughs, asymmetric ridges, or regional changes in depth; broken-line bands have fracture-zone topography, but information is not adequate for the tracing of individual lineations.

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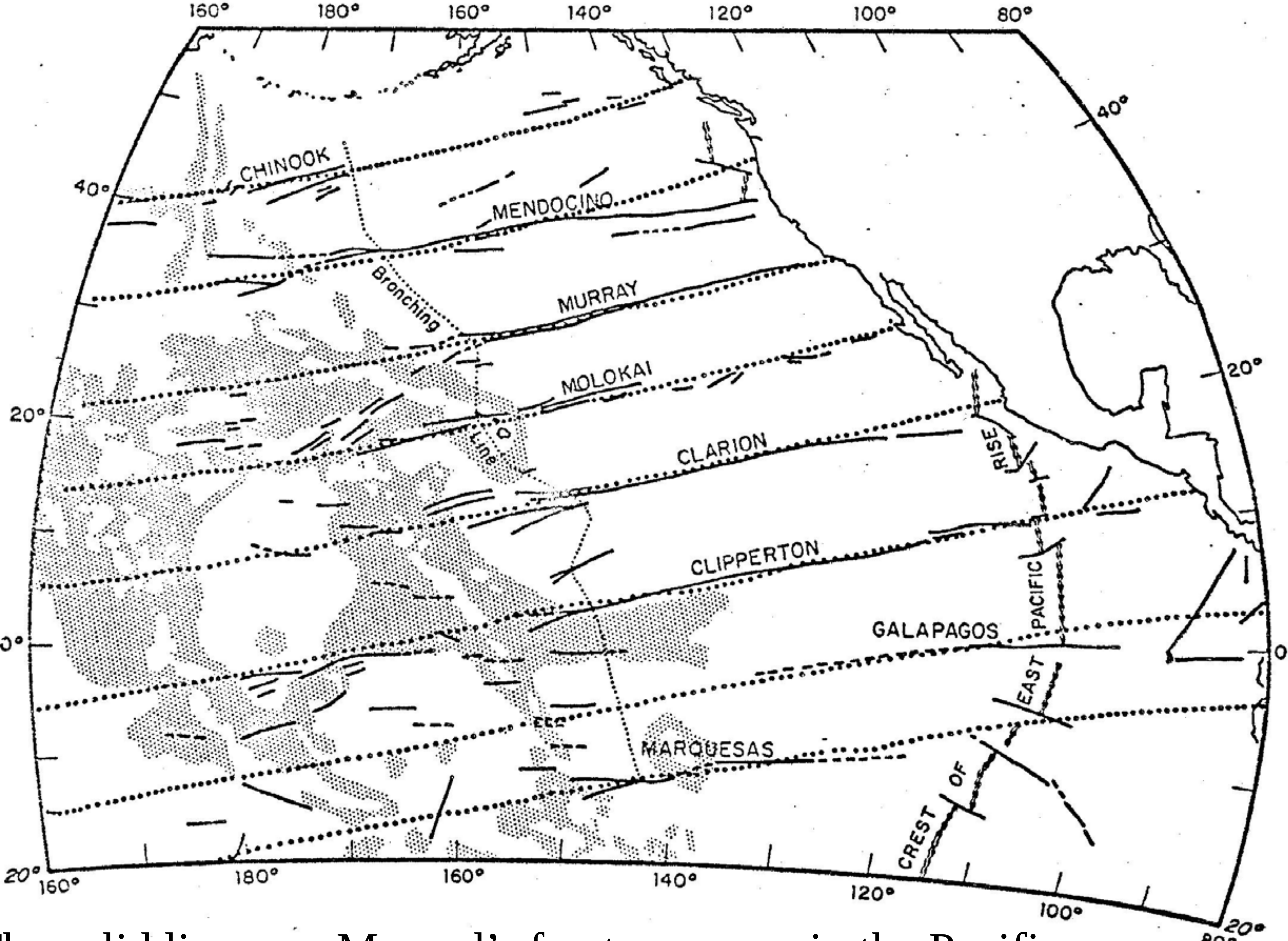


The solid lines are Menard’s fracture zones in the Pacific.
The dashed lines are small circles about a pole at 78.9°N, 111.5°E.

Figures shown at April, 1967 AGU meeting (and in handout prepared for the meeting).

Small circles concentric about pole at 62°N, 36°W compared to equatorial fracture zones mapped by Heezen and Tharp (1965)

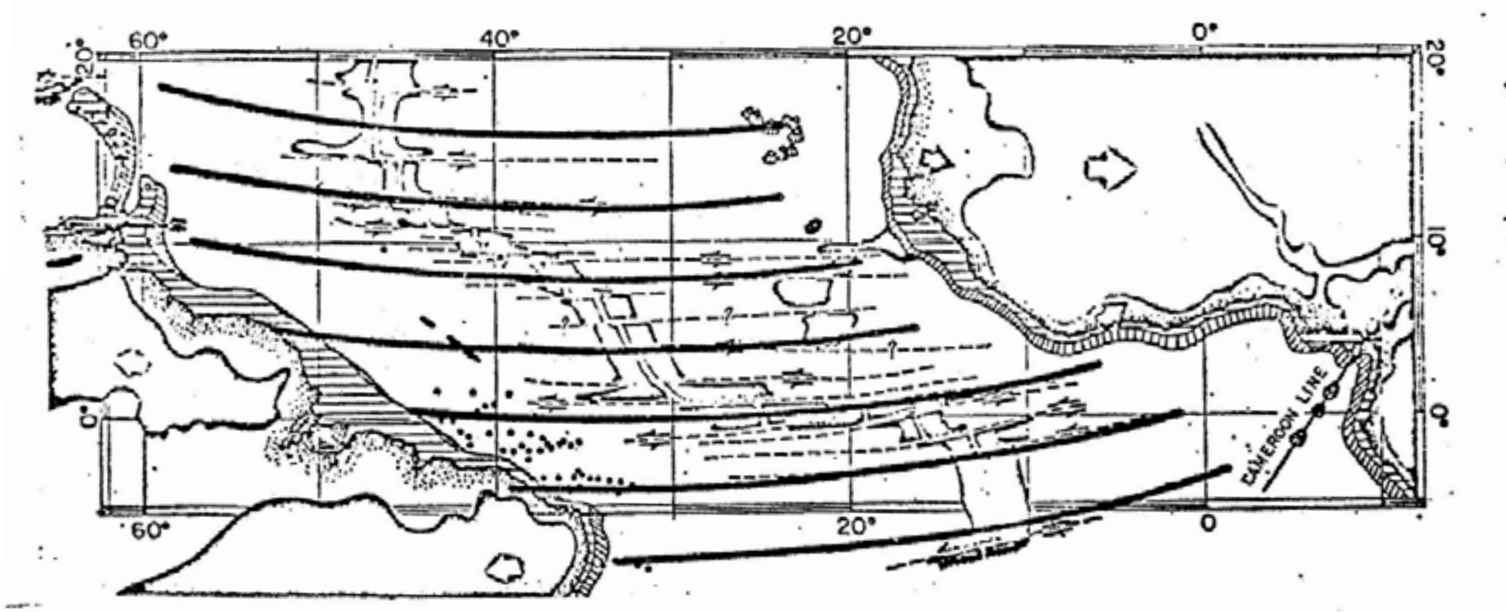
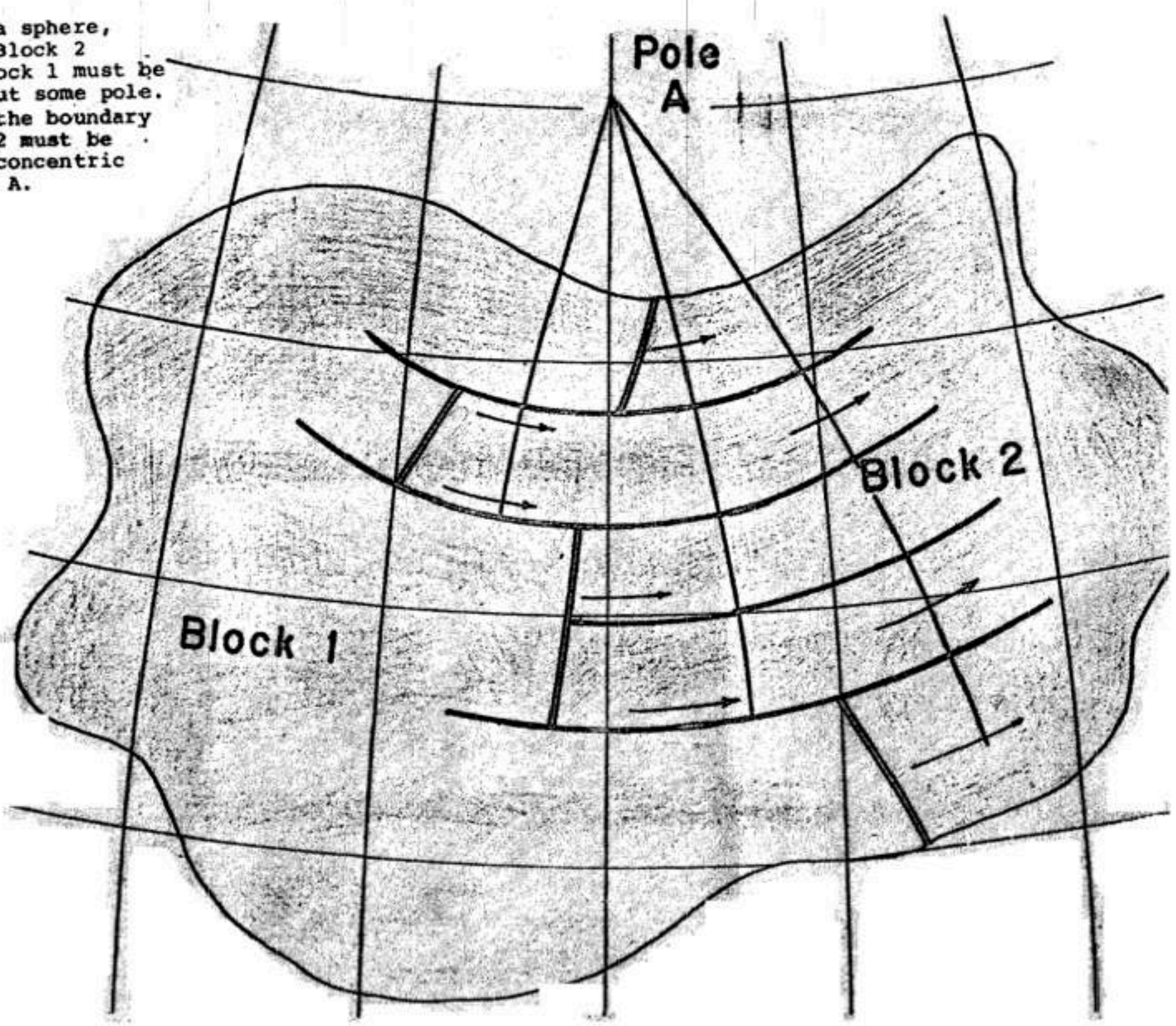


Fig. 7. The strike of the transform faults in the equatorial Atlantic are compared to circles concentric about a pole at 62°N, 36°W. These circles indicate the present motion of Africa relative to South America. [Adapted from Heezen and Tharp, 1965]

meaning of Euler Pole

Figure 4. On a sphere, the motion of Block 2 relative to Block 1 must be a rotation about some pole. All faults on the boundary between 1 and 2 must be small circles concentric about the pole A.



magnetic anomalies in Atlantic (fastest rates 90° from Euler pole)

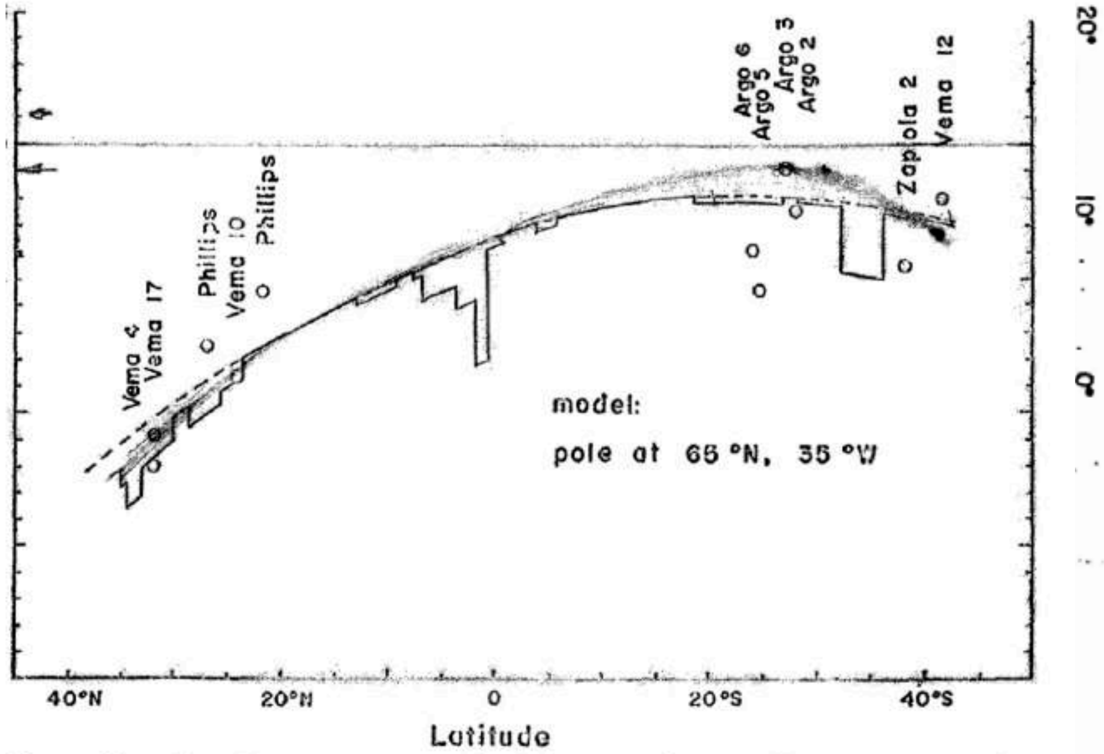


Figure 10. Spreading rates determined by magnetic anomalies are compared to the value calculated with the model.

JOURNAL OF GEOPHYSICAL RESEARCH VOL. 73, NO. 6, MARCH 15, 1968

Rises, Trenches, Great Faults, and Crustal Blocks[1]

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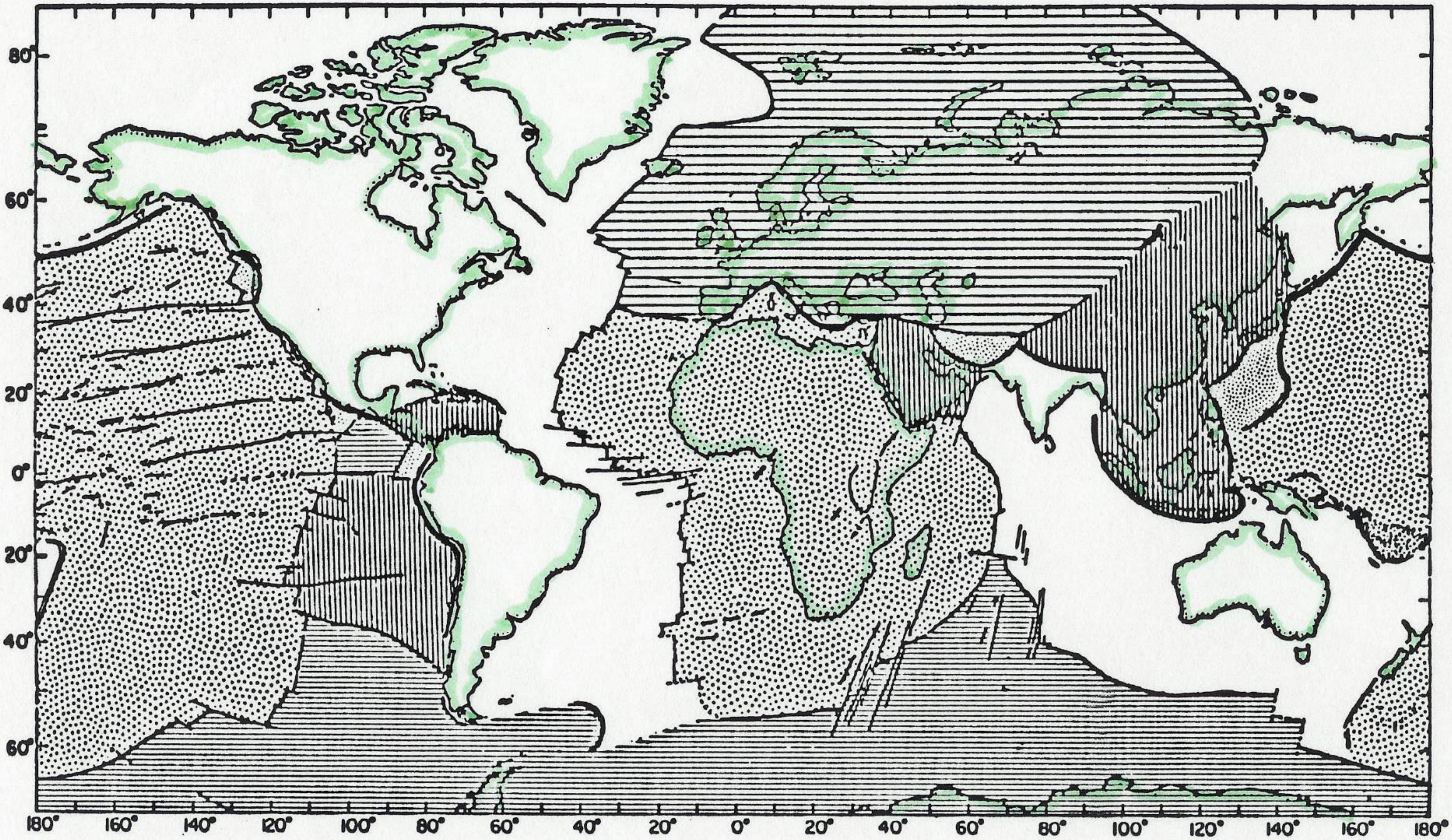
Woods Hole, Massachusetts 02543

The transform fault concept is extended to a spherical surface. The earth's surface is considered to be made of a number of rigid crustal blocks. It is assumed that each block is bounded by rises (where new surface is formed), trenches or young fold mountains (where surface is being destroyed), and great faults, and that there is no stretching, folding, or distortion of any kind within a given block. On a spherical surface, the motion of one block (over the mantle) relative to another block may then be described by a rotation of one block relative to the other block. This rotation requires three parameters, two to locate the pole of relative rotation and one to specify the magnitude of the angular velocity. If two adjacent blocks have as common boundaries a number of great faults, all of these faults must lie on 'circles of latitude' about the pole of relative rotation. The velocity of one block relative to the other must vary along their common boundary; this velocity would have a maximum at the 'equator' and would vanish at a pole of relative rotation.

The motion of Africa relative to South America is a case for which enough data are available to critically test this hypothesis. The many offsets on the mid-Atlantic ridge appear to be compatible with a pole of relative rotation at 62°N (±5°), 36°W (±2°). The velocity pattern predicted by this choice of pole roughly agrees with the spreading velocities determined from magnetic anomalies. The motion of the Pacific block relative to North America is also examined. The strike of faults from the Gulf of California to Alaska and the angles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80°
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120°
140°
160°
180°

We now make the assumption that gives this model mathematical rigor. We assume that each crustal block is perfectly rigid. If the distances between Guadalupe Island, Wake Island, and Tahiti, all within the Pacific block, were measured to the nearest centimeter and then measured again several years later, we suppose these distances would not change. The distance from Wake Island to Tokyo would, however, shorten because there is a trench between these two points, and the distance from Guadalupe Island to Mexico City would increase because there is a rise between these two points. But within the Pacific block, or any other crustal block, we shall assume there is no stretching, injection of large dikes, thickening, or any other distortion that would change distances between points. If this hypothesis is true, our conclusions will be in accord with observation. If this hypothesis is only partially valid, perhaps we will be able to assess the extent of such distortion by comparing observations with this model.

We now go to a sphere. A theorem of geometry states that a block on a sphere can be moved to any other conceivable orientation by a single rotation about a properly chosen axis. We use this theorem to prove that the relative motion of two rigid blocks on a sphere may be described by an angular velocity vector by using three parameters, two to specify the location of the pole and one for the magnitude of the angular velocity. Consider the left block in Figure 4 to be stationary and the right block to be moving as shown. Fault lines of great displacement occur where there is no component of velocity perpendicular to their strike; the strike of the fault must be parallel to the difference in velocity of the two sides. Thus, all the faults common to these two blocks must lie on small circles concentric about the pole of relative moton.

The velocity of one block relative to another will vary along their common boundary; this velocity has a maximum at the 'equator' and vanishes at the poles of rotation. It is convenient to let the 'half-velocity perpendicular

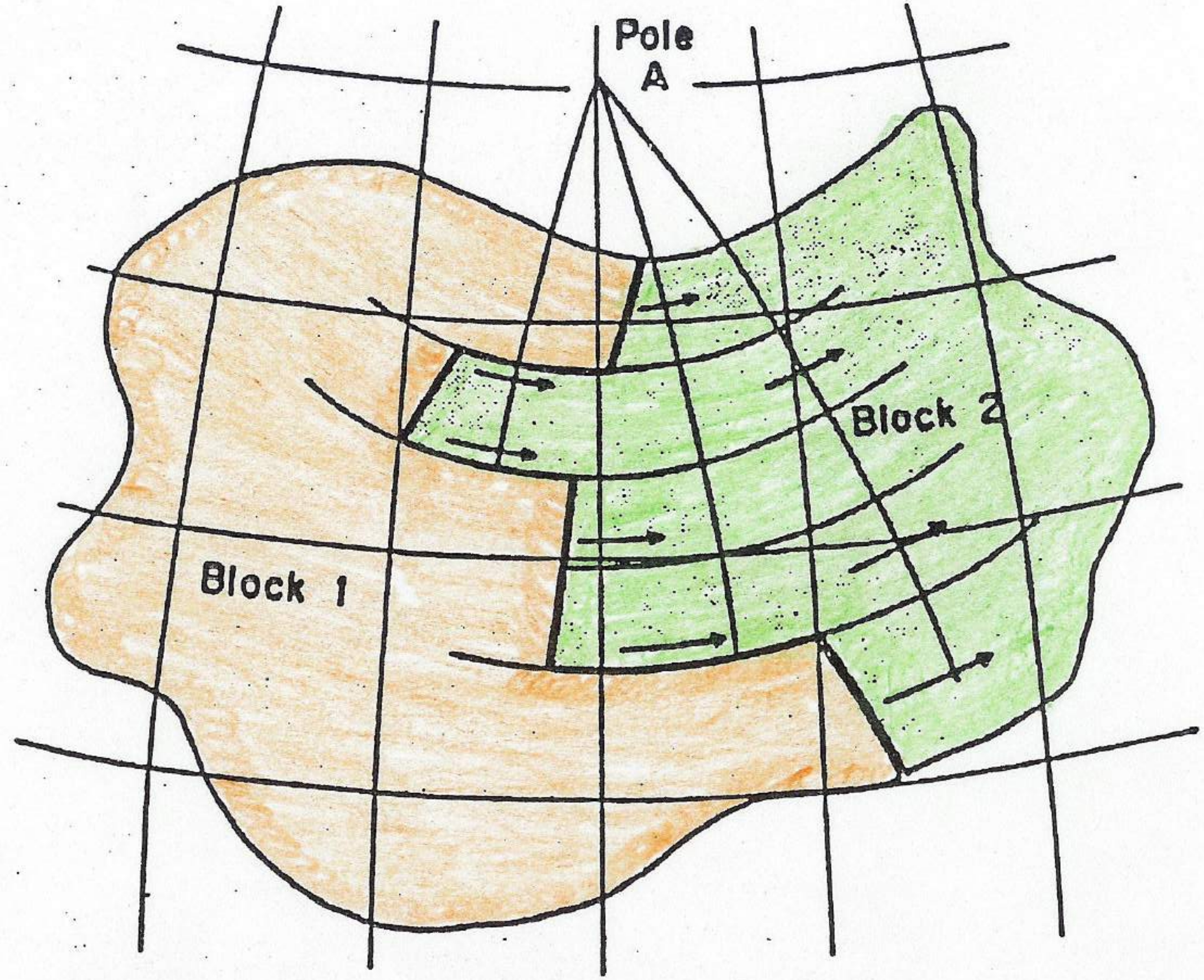
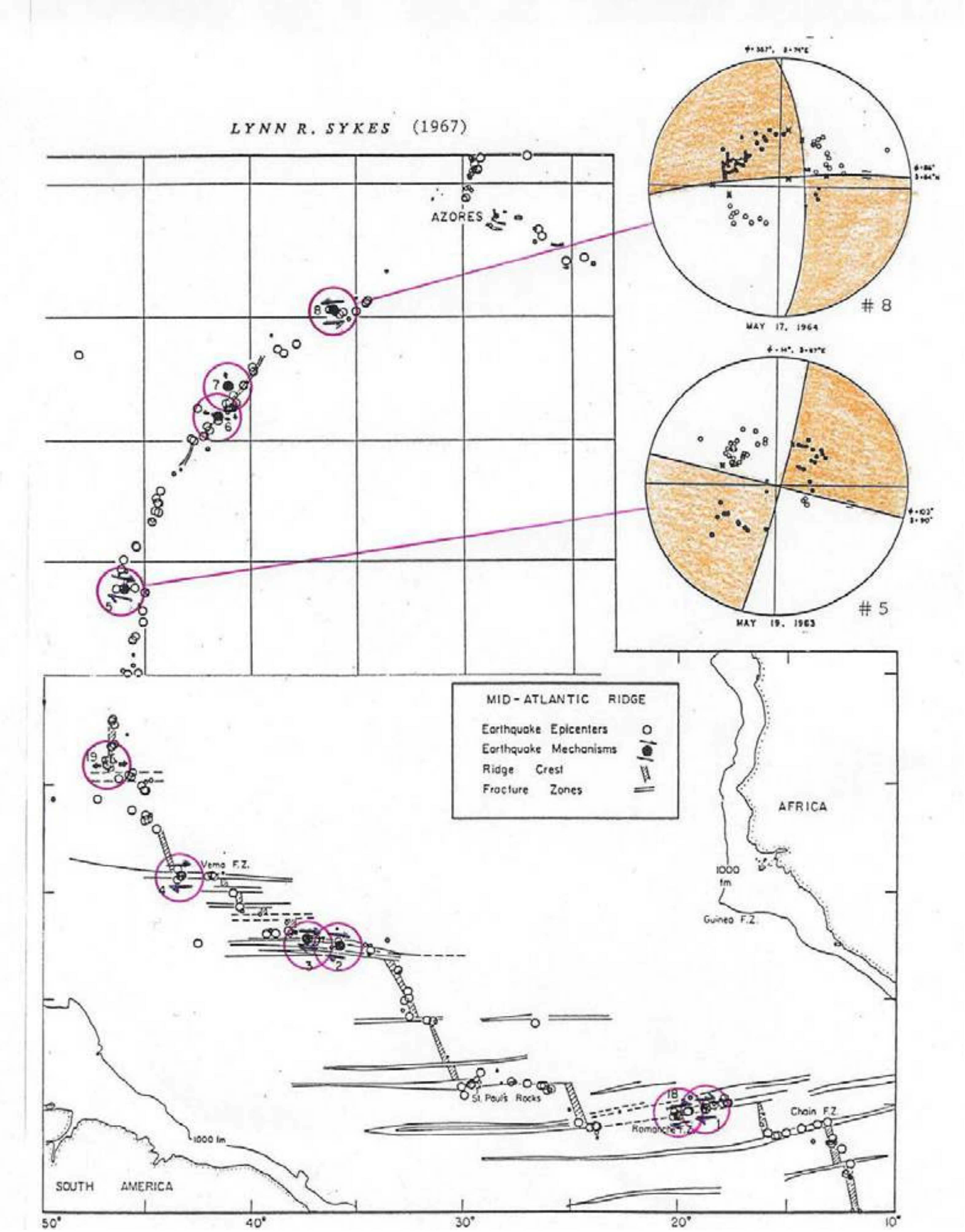


Fig. 4. On a sphere, the motion of block 2 relative to block 1 must be a rotation about some pole. All faults on the boundary between 1 and 2 must be small circles concentric about the pole A.

‘Focal Mechanism’ of earthquakes could be determined using the new world-wide, broad-band network of seismometers.

Here, Lynn Sykes (Lamont) shows the sense of motion on the offsets of the mid-Atlantic Ridge agree with the sense of motion predicted by Tuzo Wilson for ‘transform faults’.



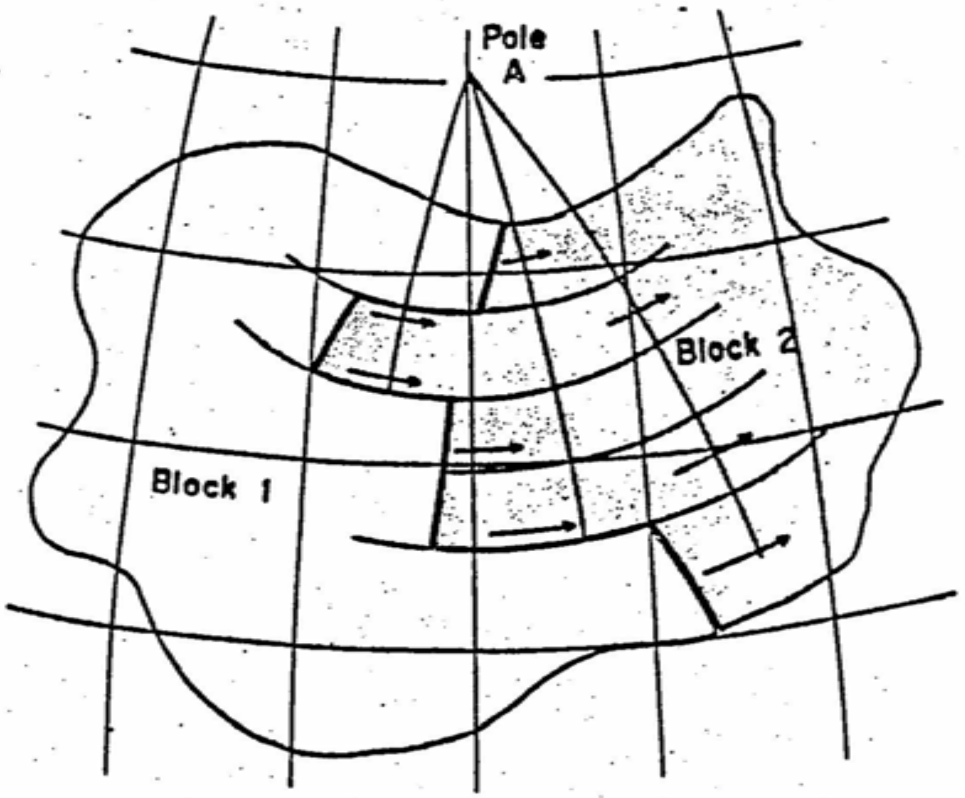


Fig. 4. On a sphere, the motion of block 2 relative to block 1 must be a rotation about some pole. All faults on the boundary between 1 and 2 must be small circles concentric about the pole A.

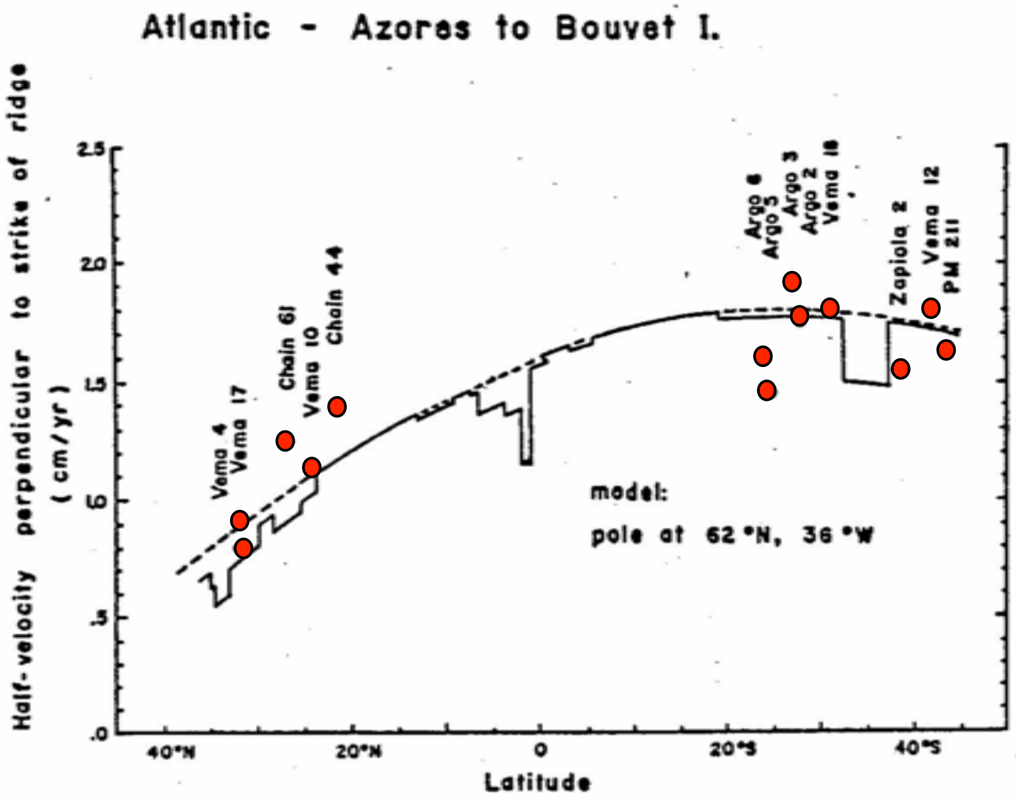

Atlantic - Azores to Bouvet I.

Fig. 9. Spreading rates determined from magnetic anomaly profiles are compared with the values caculated with the model. The solid line shows the predicted rate perpendicular to the strike of the ridge; the dashed line shows the rate parallel to the direction of spreading.

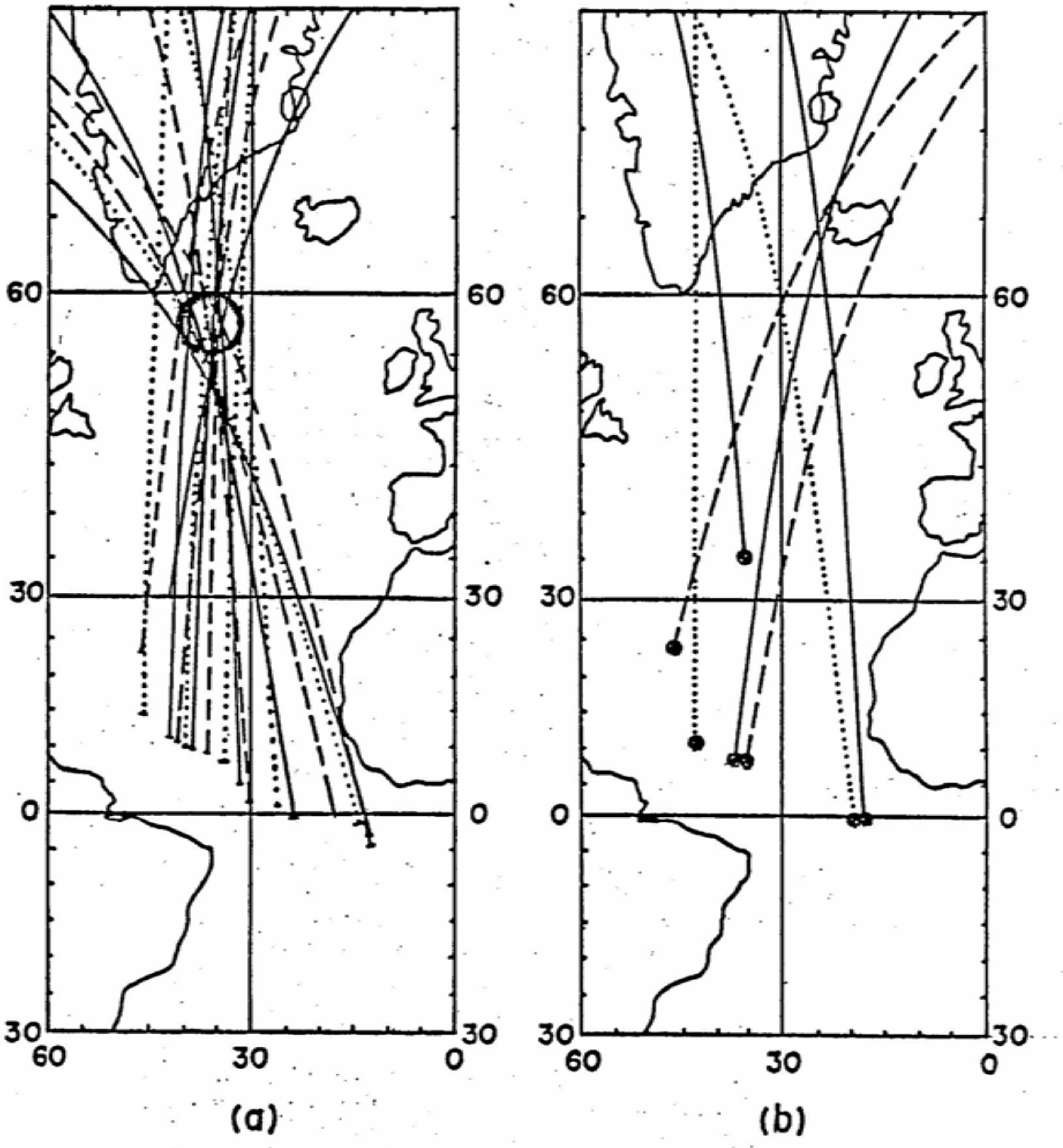


Fig. 8. Great circles perpendicular to the strike of offsets of the mid-Atlantic ridge are shown in (*a*). With one exception, all of these lines pass within the circle centered at 58°N, 36°W. Great circles perpendicular to the strike determined by earthquake mechanism solutions are shown in (*b*).

Same for the plate boundary between North America and the Pacific plates, using both fault strikes and earthquake first motions.

(Pole between these is
~ 52°N, 60°W (±10°)

(An angular rate for this motion was determined from the measured slip-rate of the San Andreas fault.)

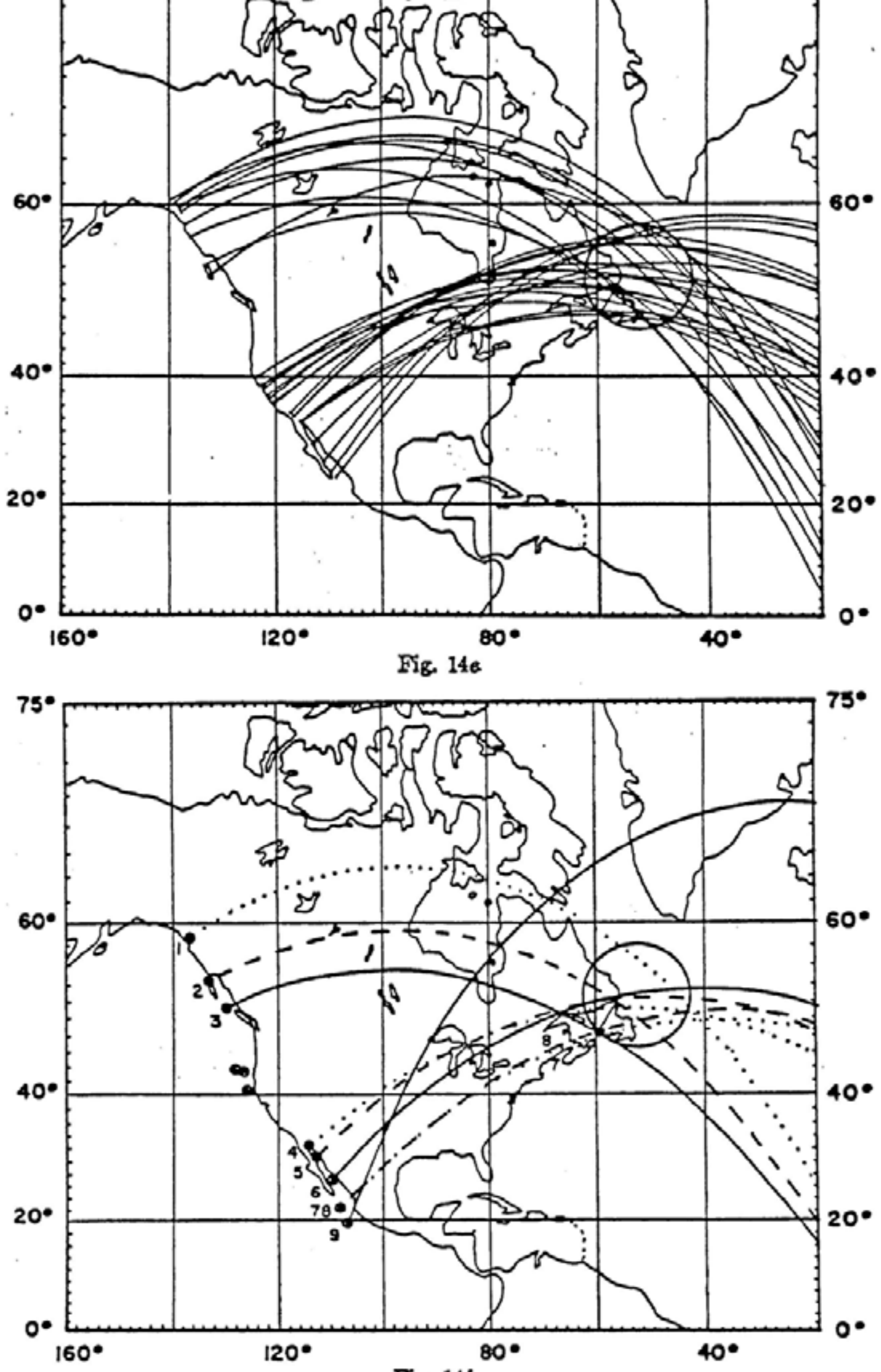


Fig. 14e

Fig. 14f

Fig. 14. Parts (*a*) through (*d*) show great circles constructed perpendicular to the strikes of fault segments observed in the Fairweather-Queen Charlotte, northern California, southern California, and Gulf of California regions. Part (*e*) is a composite of the four separate regions with the exceptions noted in the text. Part (*f*) shows great circles constructed perpendicular to strikes determined from earthquake mechanism solutions. The circle of intersection drawn has the coordinates 53°N (±6°), 53°W, (±10°).

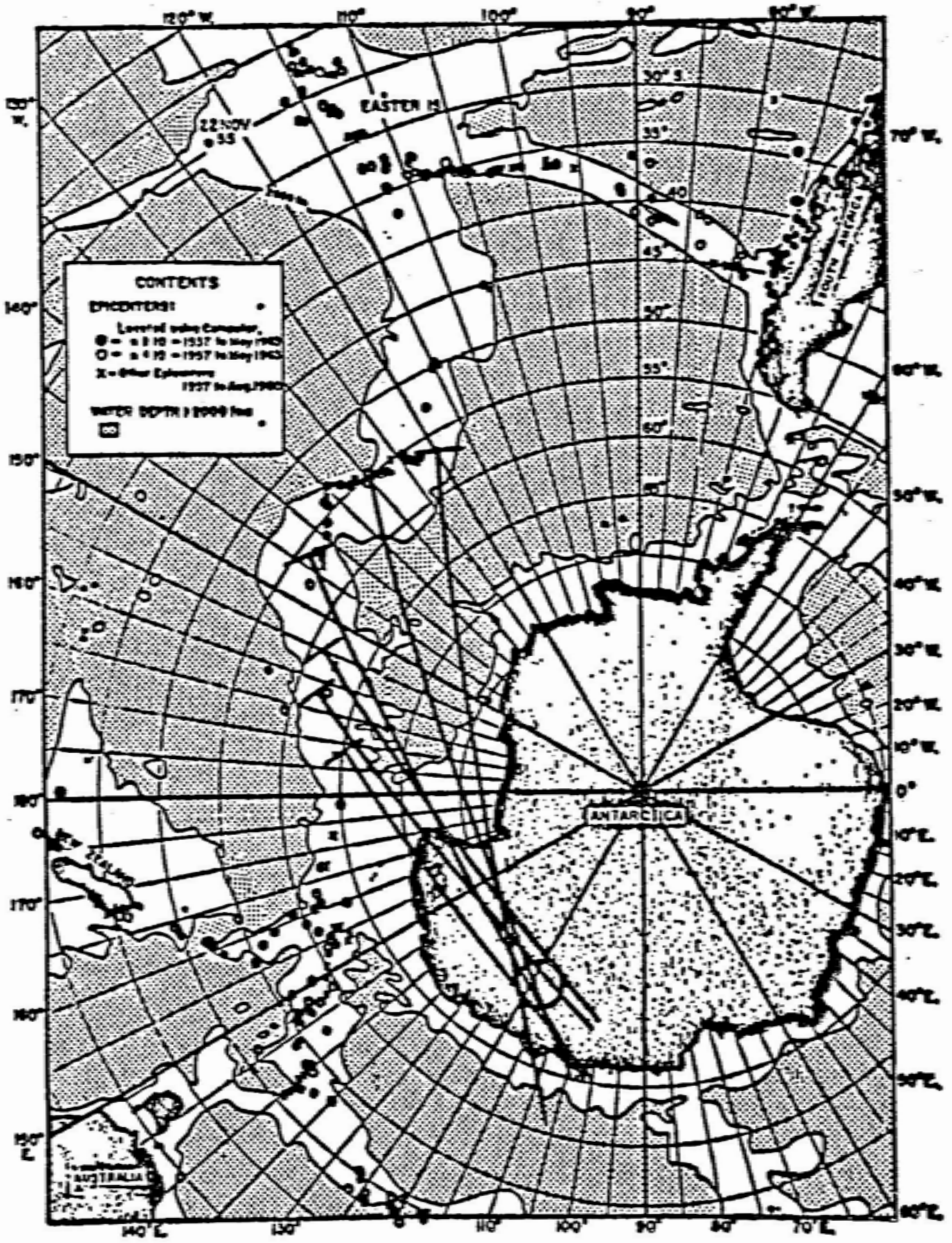


Fig. 15. Great circles constructed perpendicular to the strike of fracture zones offsetting the Pacific–Antarctic ridge are plotted on *Sykes*'s [1963] seismic map of this region. The great circles all pass within 2° of the pole at 71°S, 118°E.

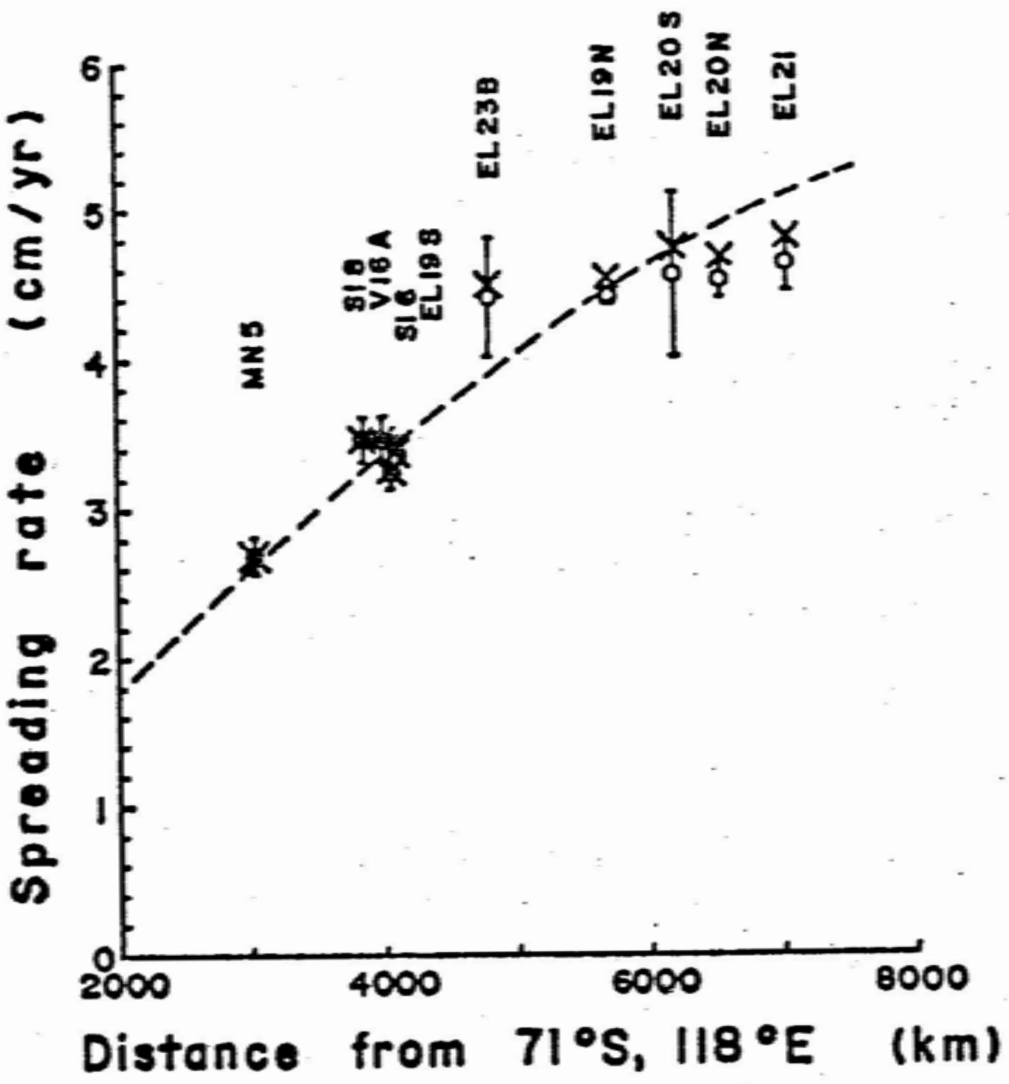


Fig. 16. Spreading rates on the Pacific-Antarctic ridge are compared with a model with $V_{max} = 5.7$ cm/yr about a pole at 71°S, 118°E. The circles are the spreading rates measured perpendicular to the strike of the ridge; the crosses are these rates projected parallel to the direction of spreading.

CONCLUSION

The evidence presented here favors the existence of large 'rigid' blocks of crust. That continental units have this rigidity has been implicit in the concept of continental drift. That large oceanic regions should also have this rigidity is perhaps unexpected. The required strength cannot be in the crust alone; the oceanic crust is too thin for this. We instead favor a strong tectosphere, perhaps 100 km thick, sliding over a weak asthenosphere. Theoretical justification for a model of this type has been advanced by *Elsasser* [1967]. In the simple two-dimensional picture of a rise and a trench with a continent between them, we imagine a conveyer-belt process in which the drifting continent need have no great strength. In the model considered here, we may have local hot spots on the rise and faster sinking at some places on the trenches. The crustal blocks should have the mechanical strength necessary to average out irregular driving sources into a uniform motion; the tectosphere should be capable of transmitting even tensile stresses. The crustal block model can possibly explain the median position of most oceanic rises and the symmetry of their magnetic pattern. We assume that the location of the rises is not fixed by some deep-seated thermal source but is determined by the motion of the blocks. Suppose a crustal block is under tension and splits along some line of weakness. The forces that tore it apart continue to act, and the blocks move apart creating a void, say, 1 km wide and 100 km deep, which is filled with mantle material. As the blocks move farther apart, they split down the center of the most recently injected dike, since this is the hottest and weakest portion between the two blocks. Even if one block remains stationary with respect to the mantle and only one block moves, we will have a symmetric pattern if a new dike is always injected up the center of the most recent dike. If the initial split was entirely within a large continental block, this control of mantle convection by boundary conditions at the top surface will result in a ridge crest with a median position.

Acknowledgments. I thank F. J. Vine for many suggestions during the formative stages of this paper, and R. L. Chase and J. D. Phillips for their careful reading of the manuscript and suggestions for its improvement. I also thank L. R. Sykes for

George Backus *(Nature)*
Feb 1964 1 page 0 fig 10 refs

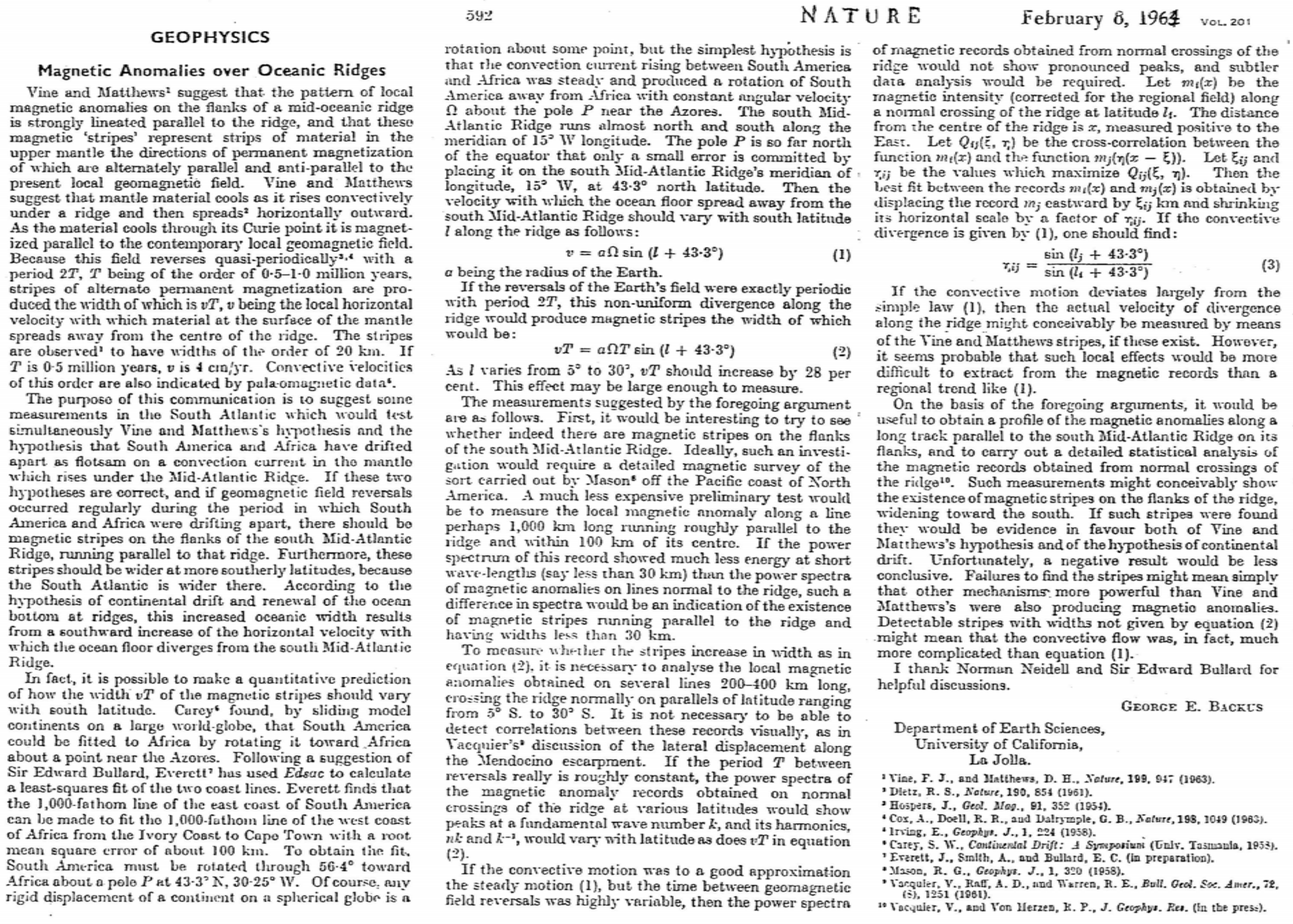
Dan McKenzie & Bob Parker *(Nature)*
Dec 1967 4 pages 6 figs 26 refs

Jason Morgan *(J. Geophys. Res)*
Mar 1968 24 pages 16 figs 35 refs 5 tables

Xavier LePichon *(J. Geophys. Res.)*
June 1968 37 pages 11 figs 68 refs 7 tables

Isacks, Oliver & Sykes *(J. Geophys. Res.)*
Sept 1968 45 pages 16 figs 154 refs 1 table

George Backus's $1\,{}^{1}/_{2}$-page letter stating Euler-pole should explain spreading rates in the South Atlantic.



GEOPHYSICS

Magnetic Anomalies over Oceanic Ridges

Vine and Matthews[1] suggest that the pattern of local magnetic anomalies on the flanks of a mid-oceanic ridge is strongly lineated parallel to the ridge, and that these magnetic 'stripes' represent strips of material in the upper mantle the directions of permanent magnetization of which are alternately parallel and anti-parallel to the present local geomagnetic field. Vine and Matthews suggest that mantle material cools as it rises convectively under a ridge and then spreads[2] horizontally outward. As the material cools through its Curie point it is magnetized parallel to the contemporary local geomagnetic field. Because this field reverses quasi-periodically[3,4] with a period $2T$, T being of the order of 0·5–1·0 million years, stripes of alternate permanent magnetization are produced the width of which is vT, v being the local horizontal velocity with which material at the surface of the mantle spreads away from the centre of the ridge. The stripes are observed[1] to have widths of the order of 20 km. If T is 0·5 million years, v is 4 cm/yr. Convective velocities of this order are also indicated by palaeomagnetic data[5].

The purpose of this communication is to suggest some measurements in the South Atlantic which would test simultaneously Vine and Matthews's hypothesis and the hypothesis that South America and Africa have drifted apart as flotsam on a convection current in the mantle which rises under the Mid-Atlantic Ridge. If these two hypotheses are correct, and if geomagnetic field reversals occurred regularly during the period in which South America and Africa were drifting apart, there should be magnetic stripes on the flanks of the south Mid-Atlantic Ridge, running parallel to that ridge. Furthermore, these stripes should be wider at more southerly latitudes, because the South Atlantic is wider there. According to the hypothesis of continental drift and renewal of the ocean bottom at ridges, this increased oceanic width results from a southward increase of the horizontal velocity with which the ocean floor diverges from the south Mid-Atlantic Ridge.

In fact, it is possible to make a quantitative prediction of how the width vT of the magnetic stripes should vary with south latitude. Carey[6] found, by sliding model continents on a large world-globe, that South America could be fitted to Africa by rotating it toward Africa about a point near the Azores. Following a suggestion of Sir Edward Bullard, Everett[7] has used *Edsac* to calculate a least-squares fit of the two coast lines. Everett finds that the 1,000-fathom line of the east coast of South America can be made to fit the 1,000-fathom line of the west coast of Africa from the Ivory Coast to Cape Town with a root mean square error of about 100 km. To obtain the fit, South America must be rotated through 56·4° toward Africa about a pole P at 43·3° N, 30·25° W. Of course, any rigid displacement of a continent on a spherical globe is a rotation about some point, but the simplest hypothesis is that the convection current rising between South America and Africa was steady and produced a rotation of South America away from Africa with constant angular velocity Ω about the pole P near the Azores. The south Mid-Atlantic Ridge runs almost north and south along the meridian of 15° W longitude. The pole P is so far north of the equator that only a small error is committed by placing it on the south Mid-Atlantic Ridge's meridian of longitude, 15° W, at 43·3° north latitude. Then the velocity with which the ocean floor spread away from the south Mid-Atlantic Ridge should vary with south latitude l along the ridge as follows:

$$v = a\Omega \sin (l + 43{\cdot}3^\circ) \qquad (1)$$

a being the radius of the Earth.

If the reversals of the Earth's field were exactly periodic with period $2T$, this non-uniform divergence along the ridge would produce magnetic stripes the width of which would be:

$$vT = a\Omega T \sin (l + 43{\cdot}3^\circ) \qquad (2)$$

As l varies from 5° to 30°, vT should increase by 28 per cent. This effect may be large enough to measure.

The measurements suggested by the foregoing argument are as follows. First, it would be interesting to try to see whether indeed there are magnetic stripes on the flanks of the south Mid-Atlantic Ridge. Ideally, such an investigation would require a detailed magnetic survey of the sort carried out by Mason[8] off the Pacific coast of North America. A much less expensive preliminary test would be to measure the local magnetic anomaly along a line perhaps 1,000 km long running roughly parallel to the ridge and within 100 km of its centre. If the power spectrum of this record showed much less energy at short wave-lengths (say less than 30 km) than the power spectra of magnetic anomalies on lines normal to the ridge, such a difference in spectra would be an indication of the existence of magnetic stripes running parallel to the ridge and having widths less than 30 km.

To measure whether the stripes increase in width as in equation (2), it is necessary to analyse the local magnetic anomalies obtained on several lines 200–400 km long, crossing the ridge normally on parallels of latitude ranging from 5° S. to 30° S. It is not necessary to be able to detect correlations between these records visually, as in Vacquier's[9] discussion of the lateral displacement along the Mendocino escarpment. If the period T between reversals really is roughly constant, the power spectra of the magnetic anomaly records obtained on normal crossings of the ridge at various latitudes would show peaks at a fundamental wave number k, and its harmonics, nk and k^{-1}, would vary with latitude as does vT in equation (2).

If the convective motion was to a good approximation the steady motion (1), but the time between geomagnetic field reversals was highly variable, then the power spectra of magnetic records obtained from normal crossings of the ridge would not show pronounced peaks, and subtler data analysis would be required. Let $m_i(x)$ be the magnetic intensity (corrected for the regional field) along a normal crossing of the ridge at latitude l_i. The distance from the centre of the ridge is x, measured positive to the East. Let $Q_{ij}(\xi, \eta)$ be the cross-correlation between the function $m_i(x)$ and the function $m_j(\eta(x - \xi))$. Let ξ_{ij} and η_{ij} be the values which maximize $Q_{ij}(\xi, \eta)$. Then the best fit between the records $m_i(x)$ and $m_j(x)$ is obtained by displacing the record m_j eastward by ξ_{ij} km and shrinking its horizontal scale by a factor of η_{ij}. If the convective divergence is given by (1), one should find:

$$\eta_{ij} = \frac{\sin (l_j + 43{\cdot}3^\circ)}{\sin (l_i + 43{\cdot}3^\circ)} \qquad (3)$$

If the convective motion deviates largely from the simple law (1), then the actual velocity of divergence along the ridge might conceivably be measured by means of the Vine and Matthews stripes, if these exist. However, it seems probable that such local effects would be more difficult to extract from the magnetic records than a regional trend like (1).

On the basis of the foregoing arguments, it would be useful to obtain a profile of the magnetic anomalies along a long track parallel to the south Mid-Atlantic Ridge on its flanks, and to carry out a detailed statistical analysis of the magnetic records obtained from normal crossings of the ridge[10]. Such measurements might conceivably show the existence of magnetic stripes on the flanks of the ridge, widening toward the south. If such stripes were found they would be evidence in favour both of Vine and Matthews's hypothesis and of the hypothesis of continental drift. Unfortunately, a negative result would be less conclusive. Failures to find the stripes might mean simply that other mechanisms more powerful than Vine and Matthews's were also producing magnetic anomalies. Detectable stripes with widths not given by equation (2) might mean that the convective flow was, in fact, much more complicated than equation (1).

I thank Norman Neidell and Sir Edward Bullard for helpful discussions.

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University of California,
La Jolla.

[1] Vine, F. J., and Matthews, D. H., *Nature*, 199, 947 (1963).
[2] Dietz, R. S., *Nature*, 190, 854 (1961).
[3] Hospers, J., *Geol. Mag.*, 91, 352 (1954).
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[5] Irving, E., *Geophys. J.*, 1, 224 (1958).
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SPACE GEODESY

VLBI - Very Long Baseline Interferometry
(Radio Telescopes and Pulsars)

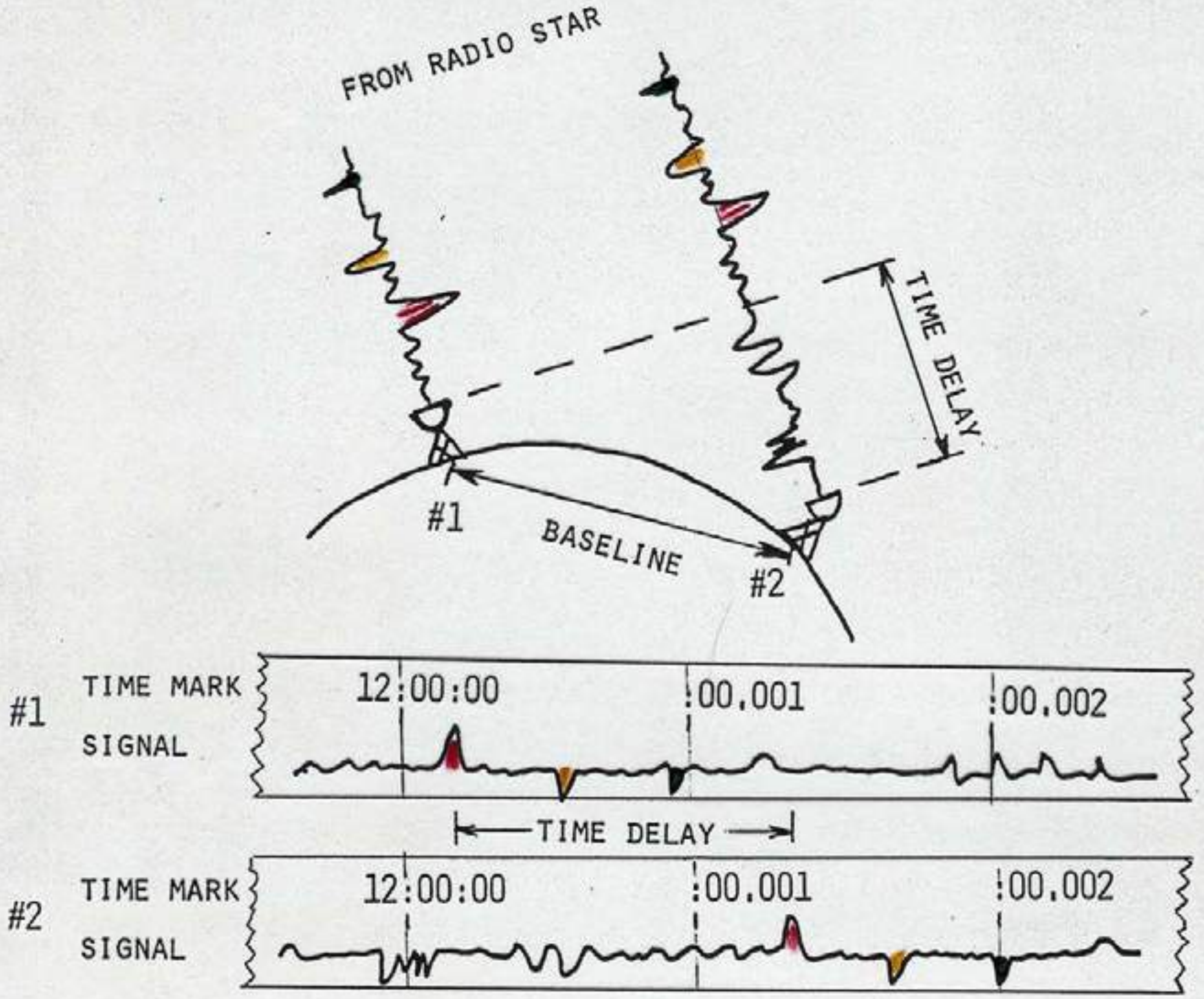
SLR - Satellite Laser Ranging
(Ground Stations that time round-trip laser-pulse to a reflecting satellite)

GPS - Global Positioning System
(Inexpensive, very portable ground radios that receive signals broadcast from a network of satellites)

These all became operational in the 1980's - but nowadays almost all measurements are made with GPS.

Also GLONAS {a Russian equivalent of GPS}, GALILEO {a European Union equivalent of GPS}, and DORIS {a French 'inverse GPS'}

VLBI VERY LONG BASELINE INTERFEROMETRY

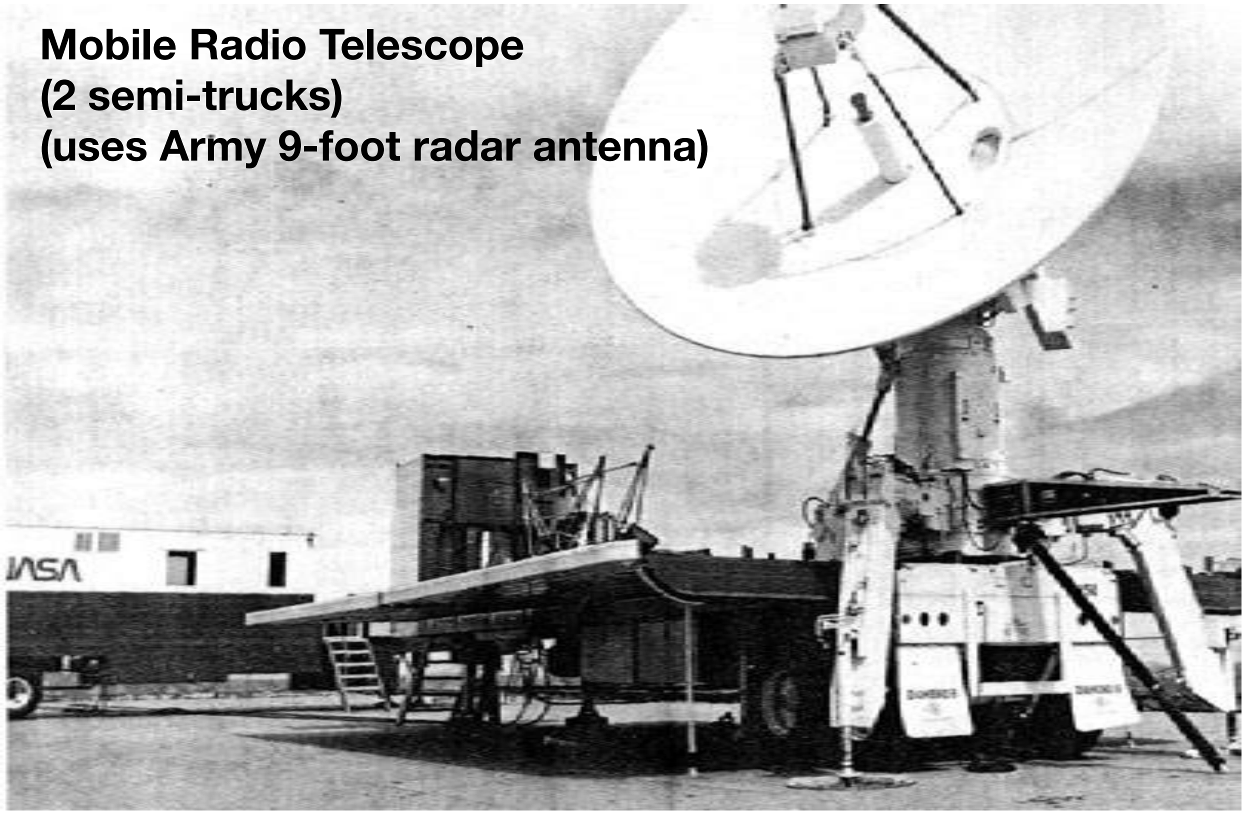


REQUIREMENTS:

- 2 (OR MORE) RADIOTELESCOPES LOOKING AT SAME STAR.
- "PERFECT" CLOCKS (HYDROGEN MASERS). .03 NSEC = 1 CM
- BROADBAND TAPE RECORDERS TO RECORD "NOISE BURSTS" FROM STAR (ABOUT 1 COMPUTER TAPE FILLED PER 5 MINUTES).

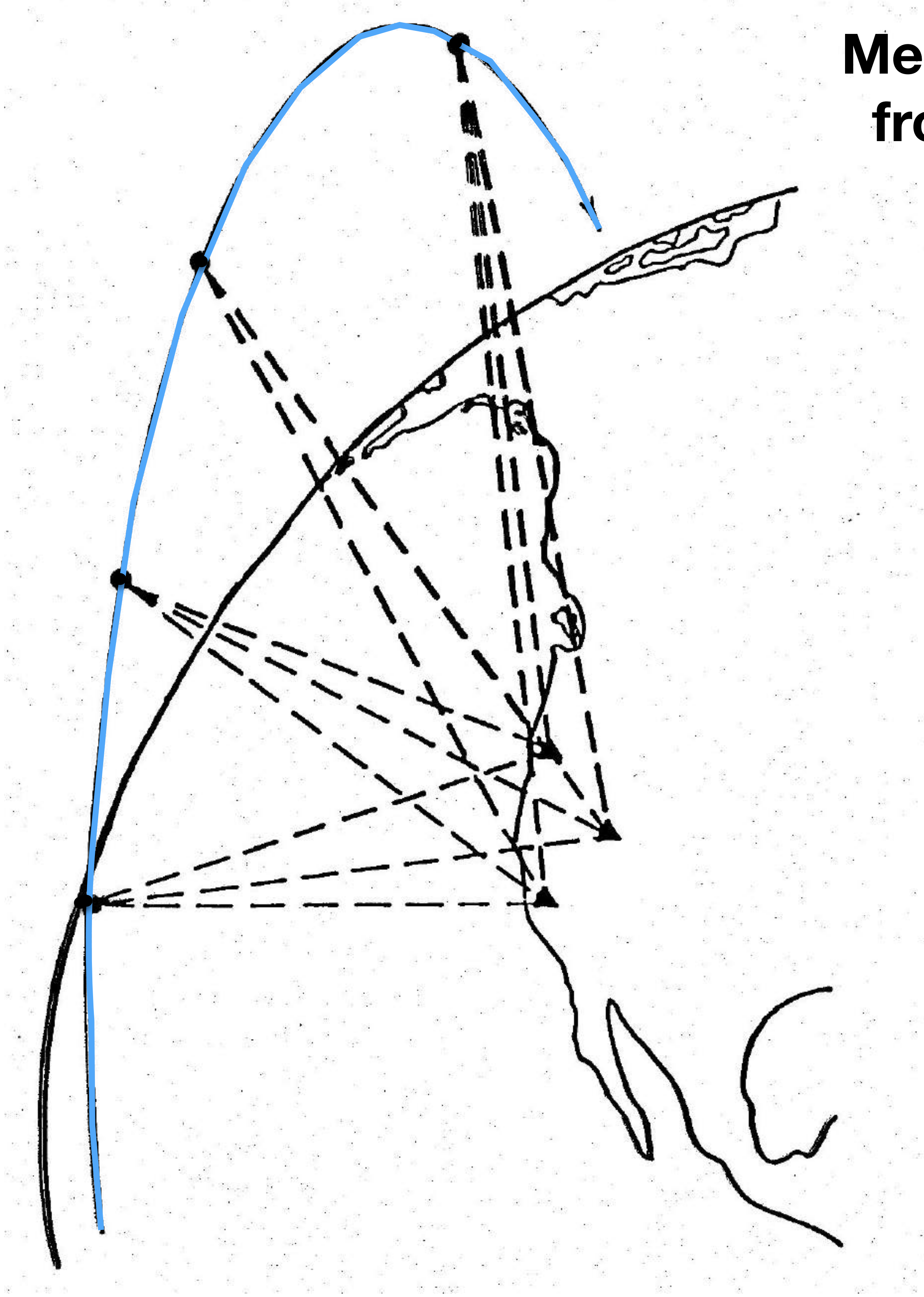
SEND BOTH TAPES TO "CORRELATOR", FROM HOW TIME-DELAY CHANGES THROUGH THE DAY, COMPUTE "BASELINE".

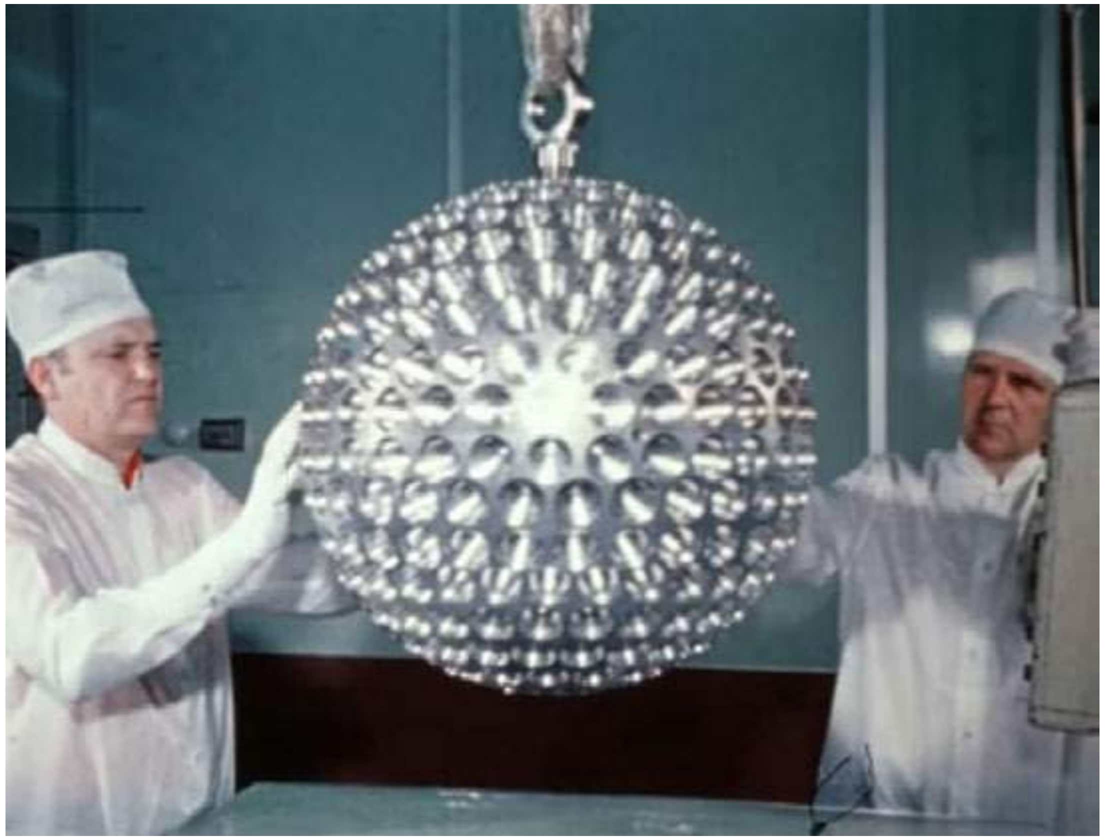
Haystack Observatory (MIT) Westford, MA

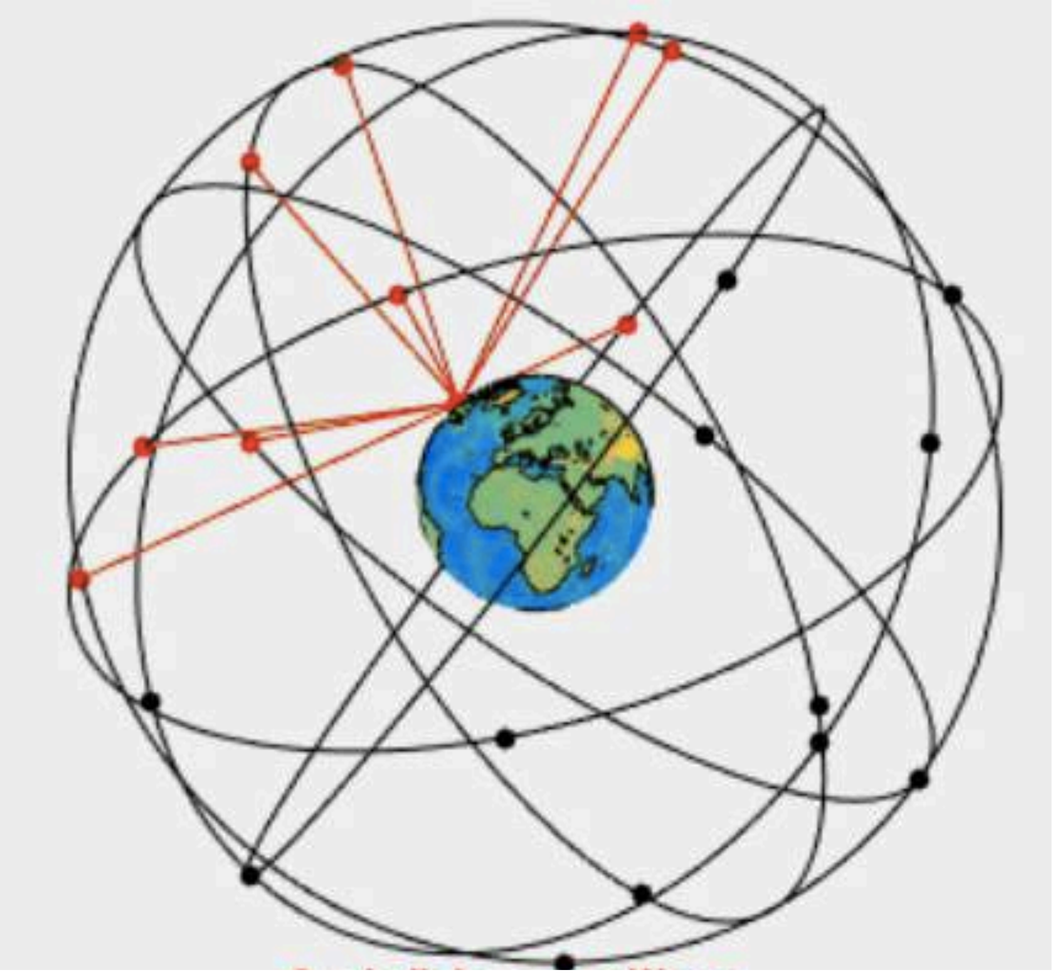

Mobile Radio Telescope
(2 semi-trucks)
(uses Army 9-foot radar antenna)

SLR Satellite Laser Ranging

Measure roundtrip time-of-flight
from ground station to satellite

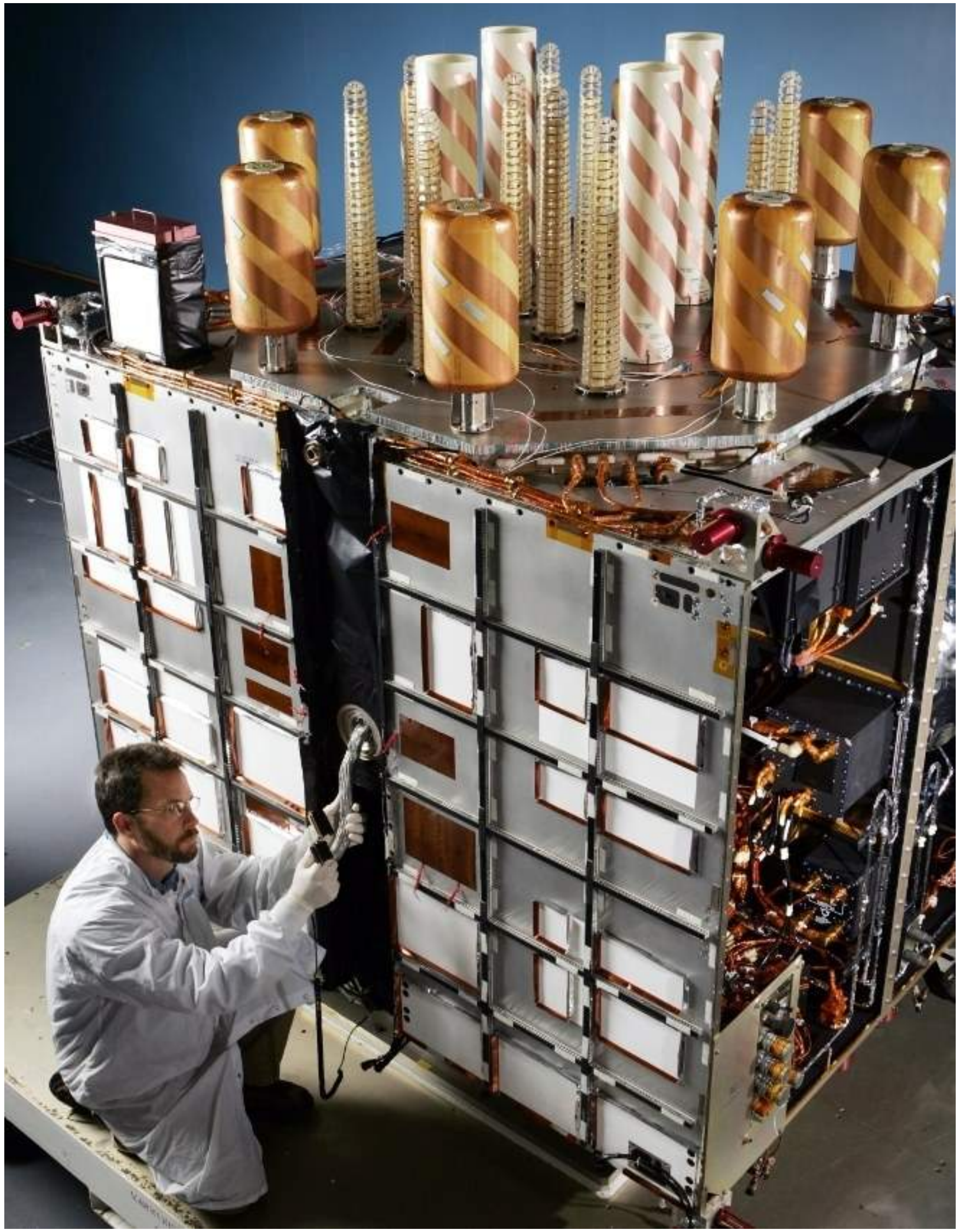






9 satellites visible at any moment

Operating cost: ~ $2 million/day
each: ~$ 40 million to build + $ 50 million to launch
to put initial constellation in orbit: ~$ 2 billion
weight: ~ 1 Ton lifespan: ~ 12 years



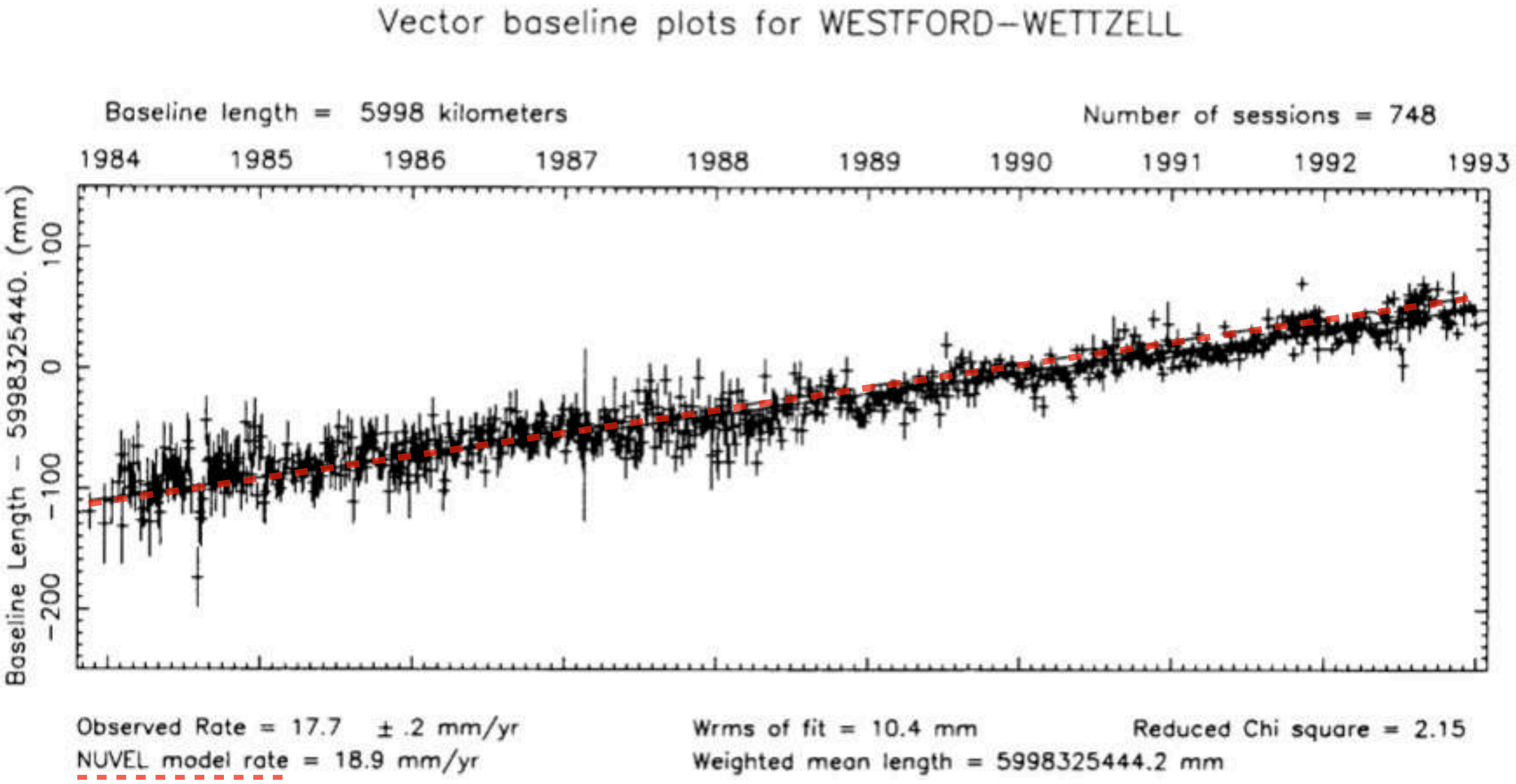
Global Positioning System

31 satellites
orbit radius: 20,000 km, 12,000 miles
orbit period: 12 hr
10 ground tracking stations (worldwide)

Each satellite has an atomic clock, and broadcasts radio pulses accurate to several picoseconds.
The pulses contain a code giving orbit to several millimeter accuracy

VLBI baseline-change measurements (17.7 ± .2 mm/yr)
compared to magnetic-anomaly prediction (18.9 mm/yr)

(Westford, Massachusetts to Wettzell, Germany)



Vector baseline plots for WESTFORD–WETTZELL

Baseline length = 5998 kilometers

Number of sessions = 748

Observed Rate = 17.7 ± .2 mm/yr

NUVEL model rate = 18.9 mm/yr

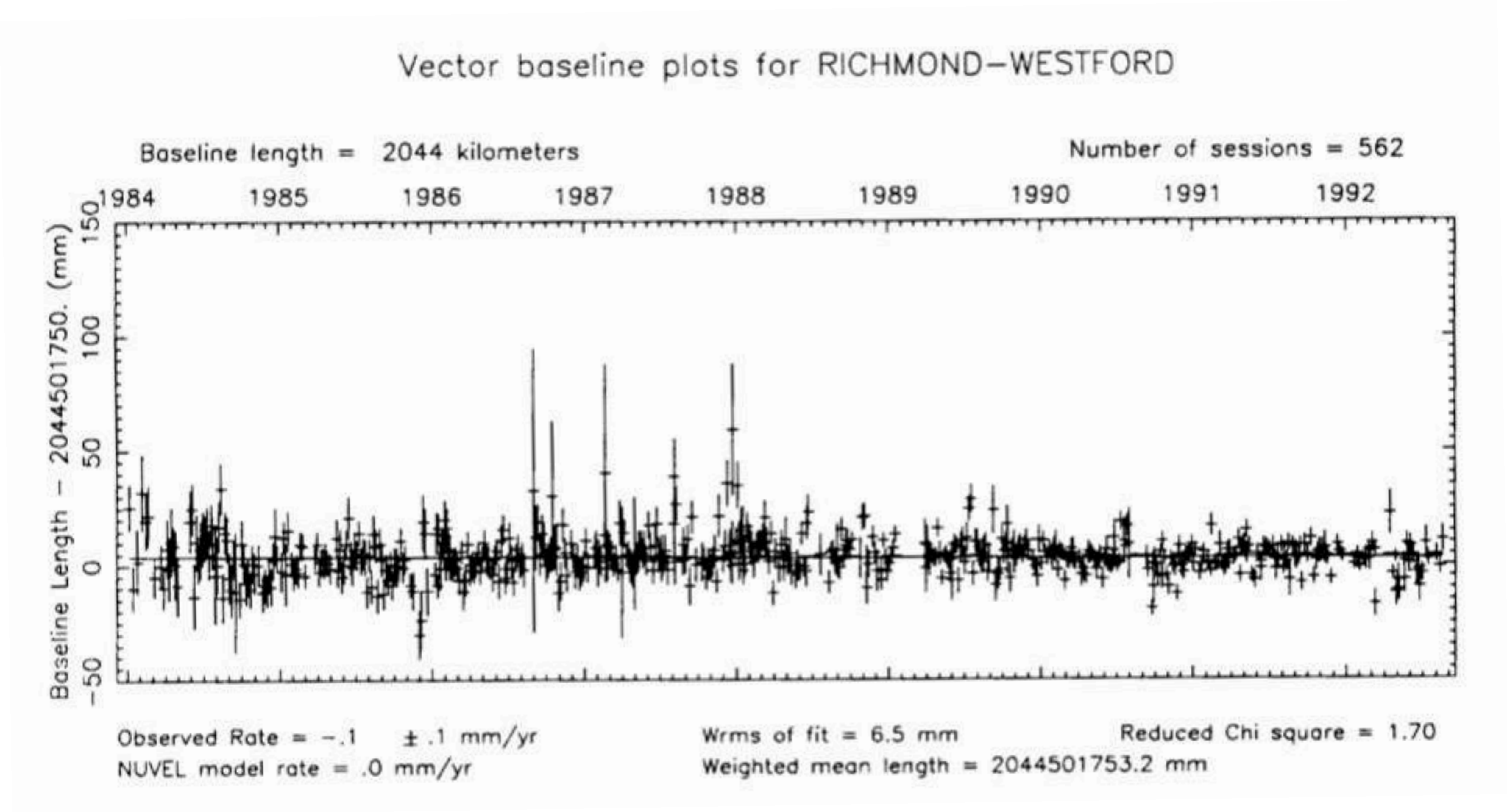
Wrms of fit = 10.4 mm

Weighted mean length = 5998325444.2 mm

Reduced Chi square = 2.15

VLBI baseline-change measurements (-.1 ± .1 mm/yr)
compared to magnetic-anomaly prediction (zero, same plate)

(Richmond, Florida to Westford, Massachusetts)



Vector baseline plots for RICHMOND–WESTFORD

Baseline length = 2044 kilometers

Number of sessions = 562

Observed Rate = –.1 ± .1 mm/yr

NUVEL model rate = .0 mm/yr

Wrms of fit = 6.5 mm

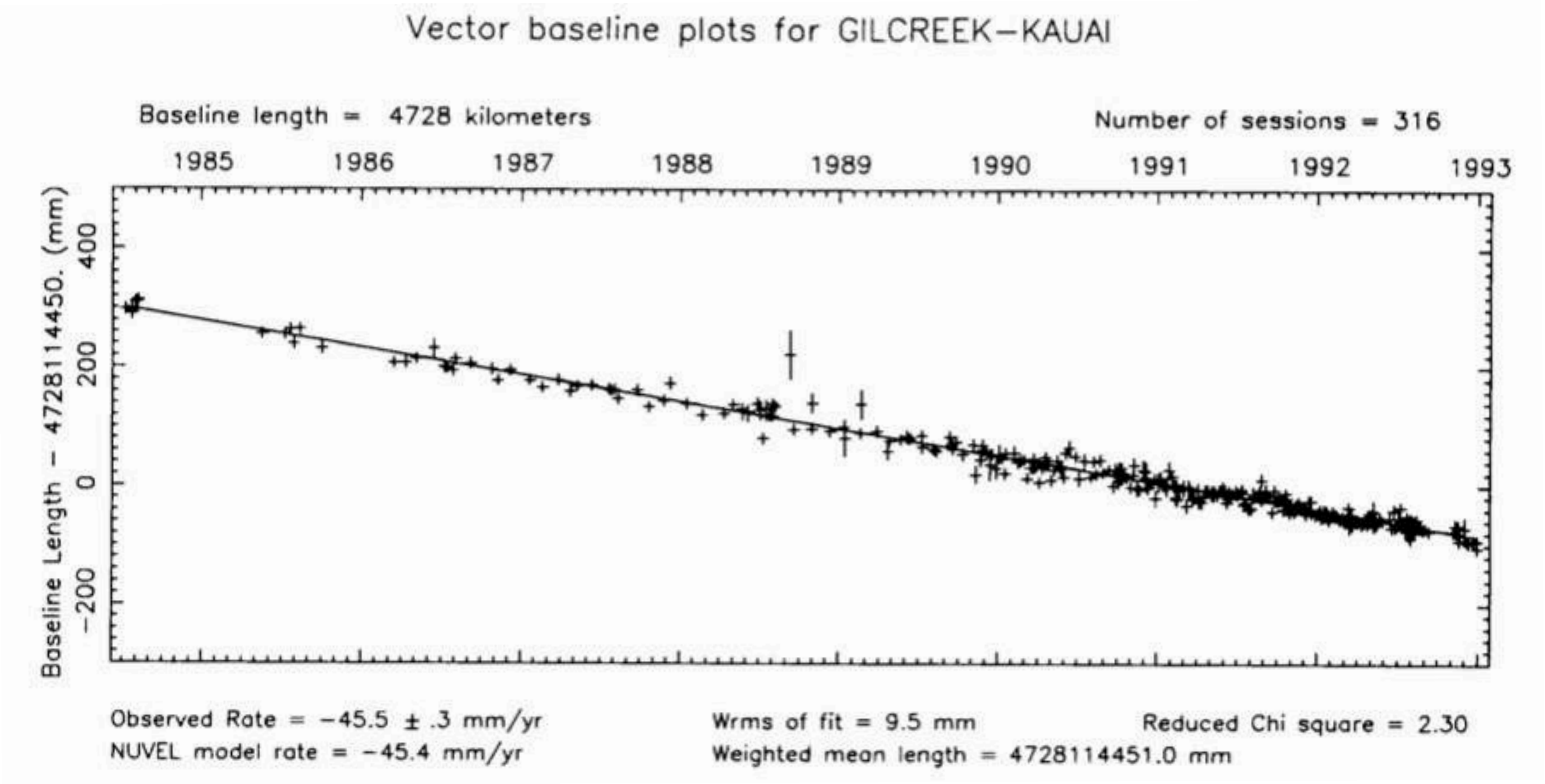
Weighted mean length = 2044501753.2 mm

Reduced Chi square = 1.70

(The Richmond antenna was blown-down
by Hurricane Andrew in 1992)

VLBI baseline-change measurements : (-45.5 ± .3 mm/yr)
compared to magnetic-anomaly prediction : (-45.4 mm/yr)

(Gilcreek, Alaska to Kauai, Hawaii)



(There's a deep-sea trench between Alaska and Hawaii, thus no direct magnetic-anomaly data to obtain a closure rate — this is purely a prediction based on rigid-plates and the worldwide pattern of magnetic anomalies between spreading plates.)

(1994) - VLBI measurements of motion (with the error ellipses) compared to the NUVEL (magnetic anomaly) model (no error shown).

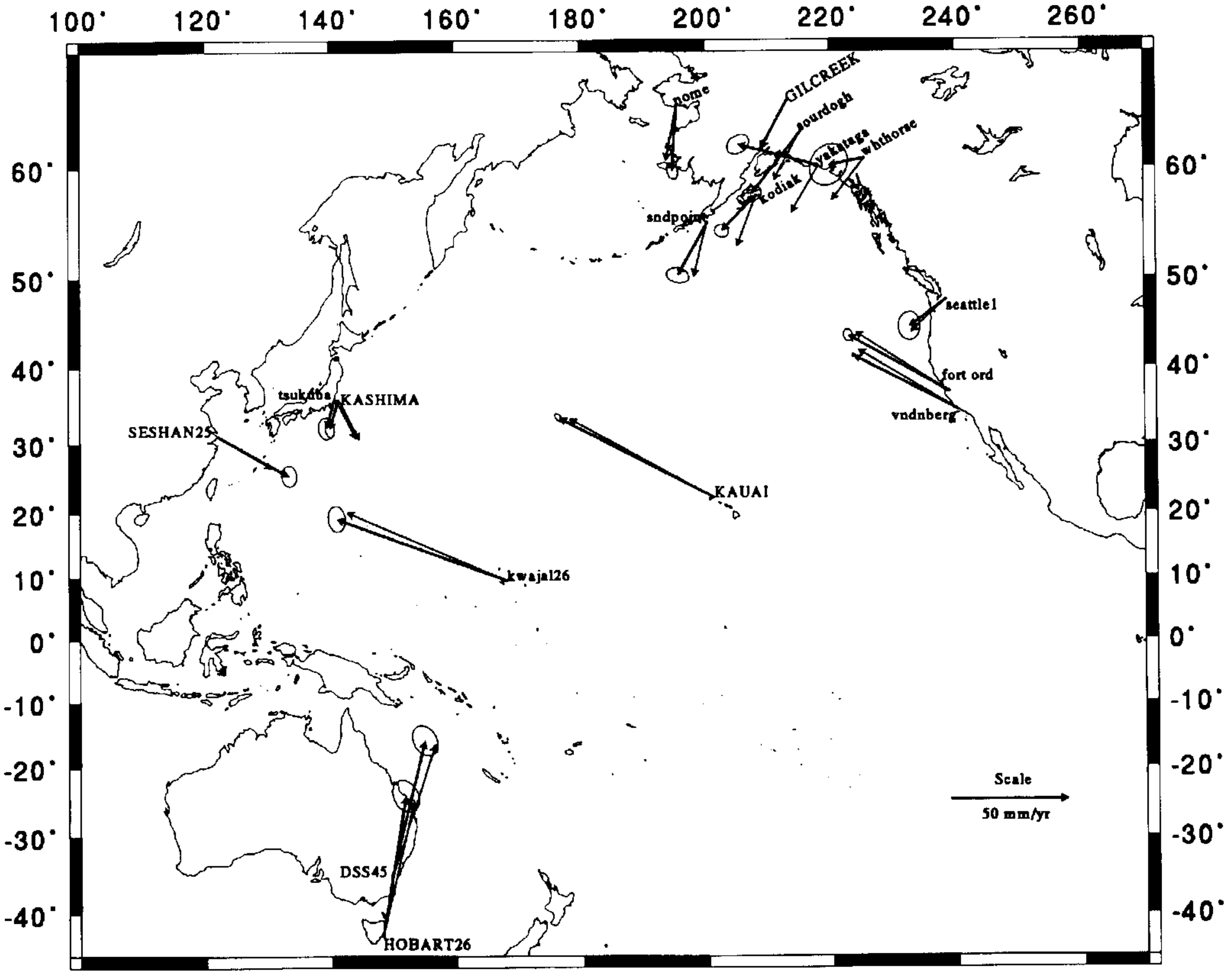


Figure 4. Pacific site velocities (3-sigma error ellipses) from GLB 907.

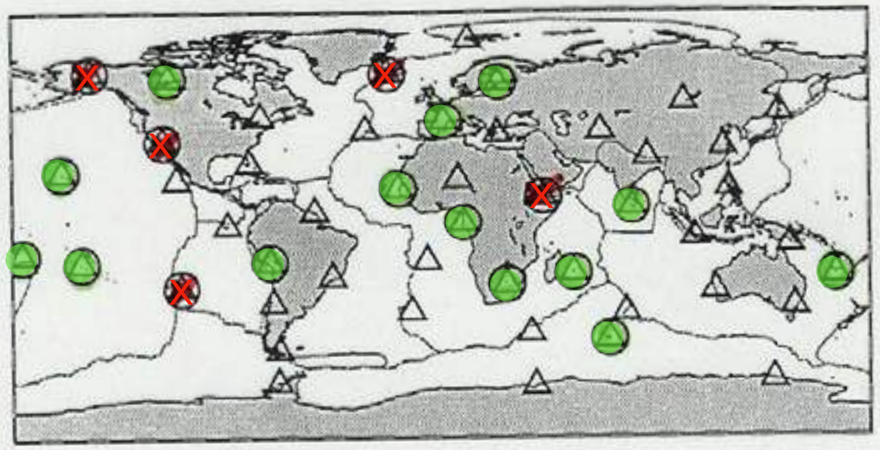
(DORIS antenna at Greenbelt, Maryland)

Comparison of motions of DORIS land stations (a French geodetic satellite system) to the predictions of ‘NUVEL-1’ plate velocities (magnetic anomaly based). (Soudarin & Cazenave, 1995)

GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 4, PAGES 469-472, FEBRUARY 15, 1995

Large-Scale tectonic plate motions measured with the DORIS space geodesy system

Laurent Soudarin and Anny Cazenave GRGS-CNES, 18 av E.Belin, Toulouse, France



‘Red’ stations not used — near plate boundaries

Figure 1. Map of the DORIS network. The circles indicate the 19 sites considered in this study.

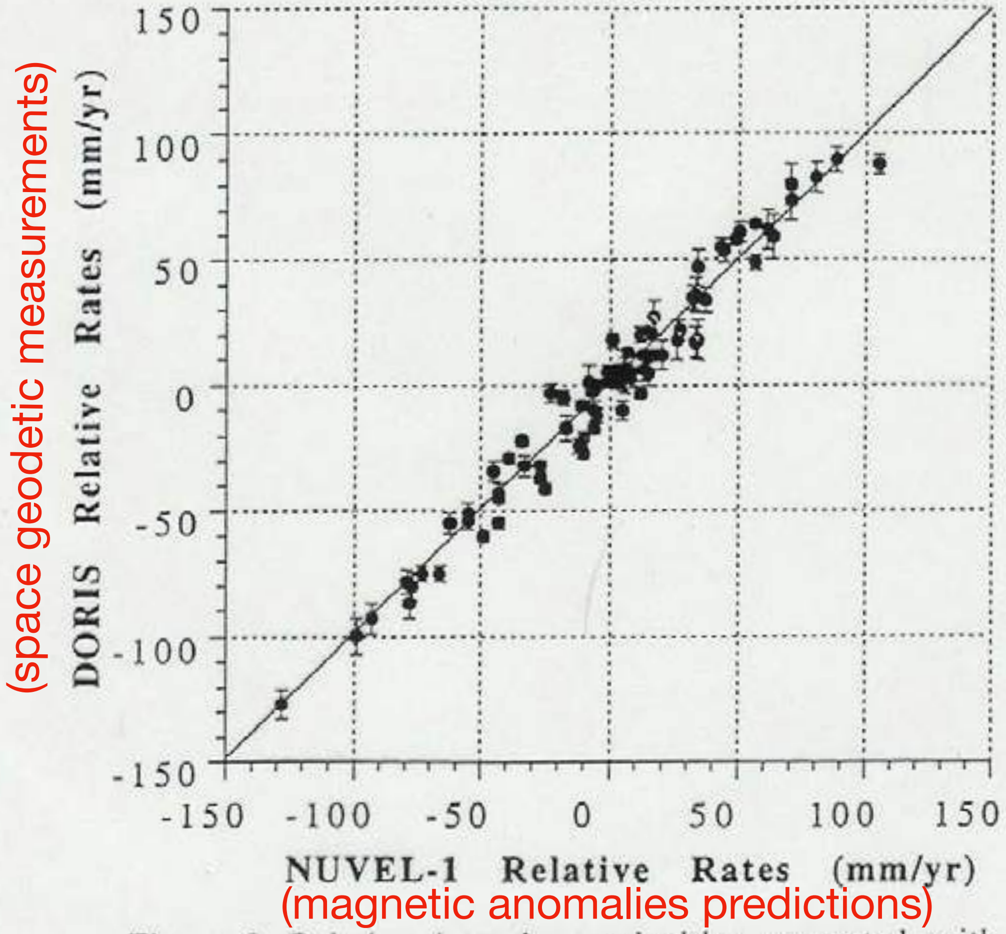


Figure 3. Relative interplate velocities computed with DORIS and compared to NUVEL-1. These concern all sites listed in Table 1 (except the sites of Fairbanks, Reykjavik, Easter Island, Djibouti and Goldstone).

So, by ~1990, direct measurements of distances of points measured by space-geodetic techniques were showing excellent agreement with the velocities predicted by rigid-plates & magnetic anomalies. (Note, anomalies appear only at mid-ocean ridges thus there were no velocity data at convergent trenches or of possible distortion within plates.)

But even earlier, evidence was beginning to challenge the 'rigid-plate' hypothesis. You 'knew' there were zones within plates that were deforming — China-East Asia was always regarded as mysterious; but with no data, nothing could be said.

D. P. McKenzie, Plate Tectonics of the Mediterranean Region, Nature 266, 1970

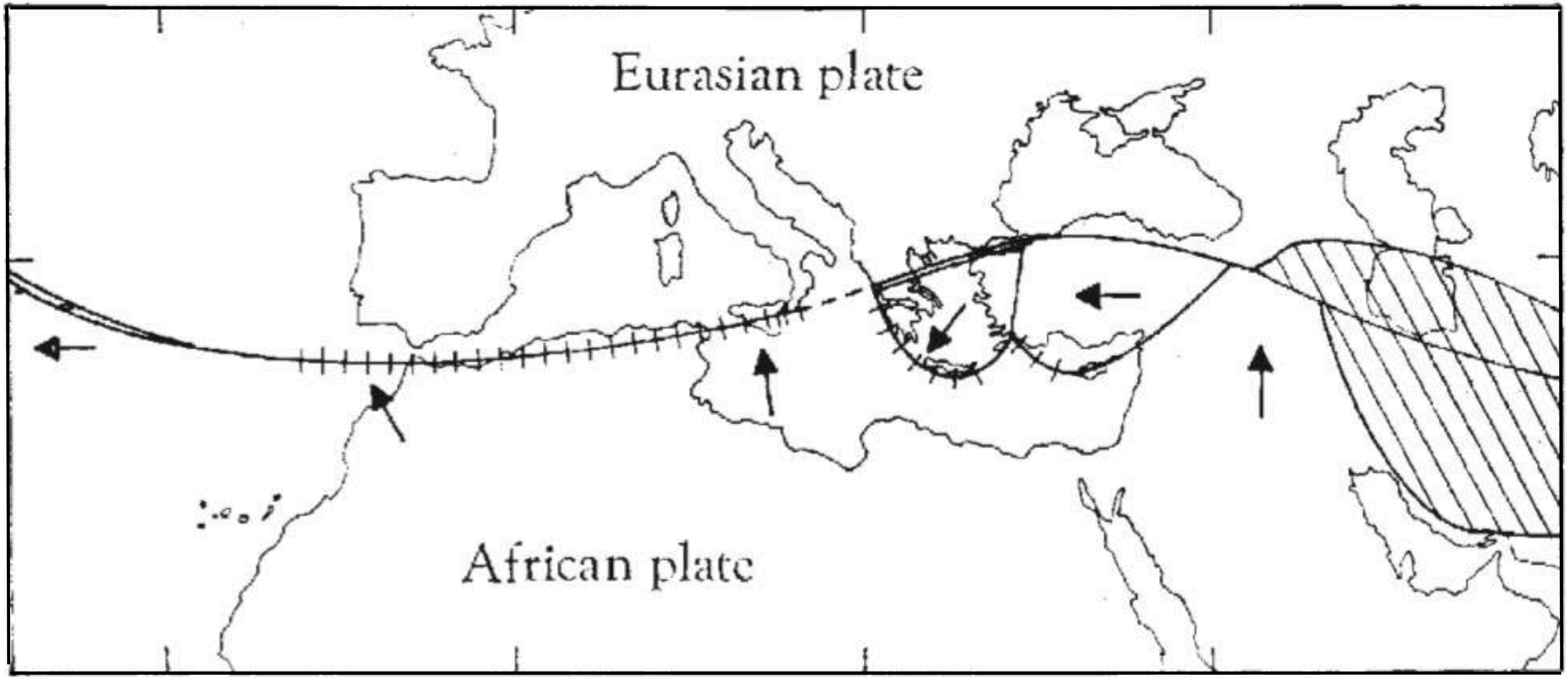


Fig. 4. Approximate positions of plate boundaries at present active, with arrows marking the directions of motion relative to the Eurasian plate. Boundaries creating lithosphere are shown with a double line, boundaries consuming plates with short lines at right-angles to them. The cross-hatched region in Eastern Turkey and Iran is seismically active throughout. Fault plane solutions here are all overthrusts (Fig. 2), and show that the crust is being thickened all over this region. Most major shocks within the cross-hatched area occur on major active faults mapped by Wellman[28] from aerial photographs and shown as solid lines.

LePichon, Chamot-Rooke, Lallemant, Noomen & Veis, J. Geophys. Res., 1995

(Measurements showing the ‘pumpkin-seed’ tectonics of Turkey and Greece)

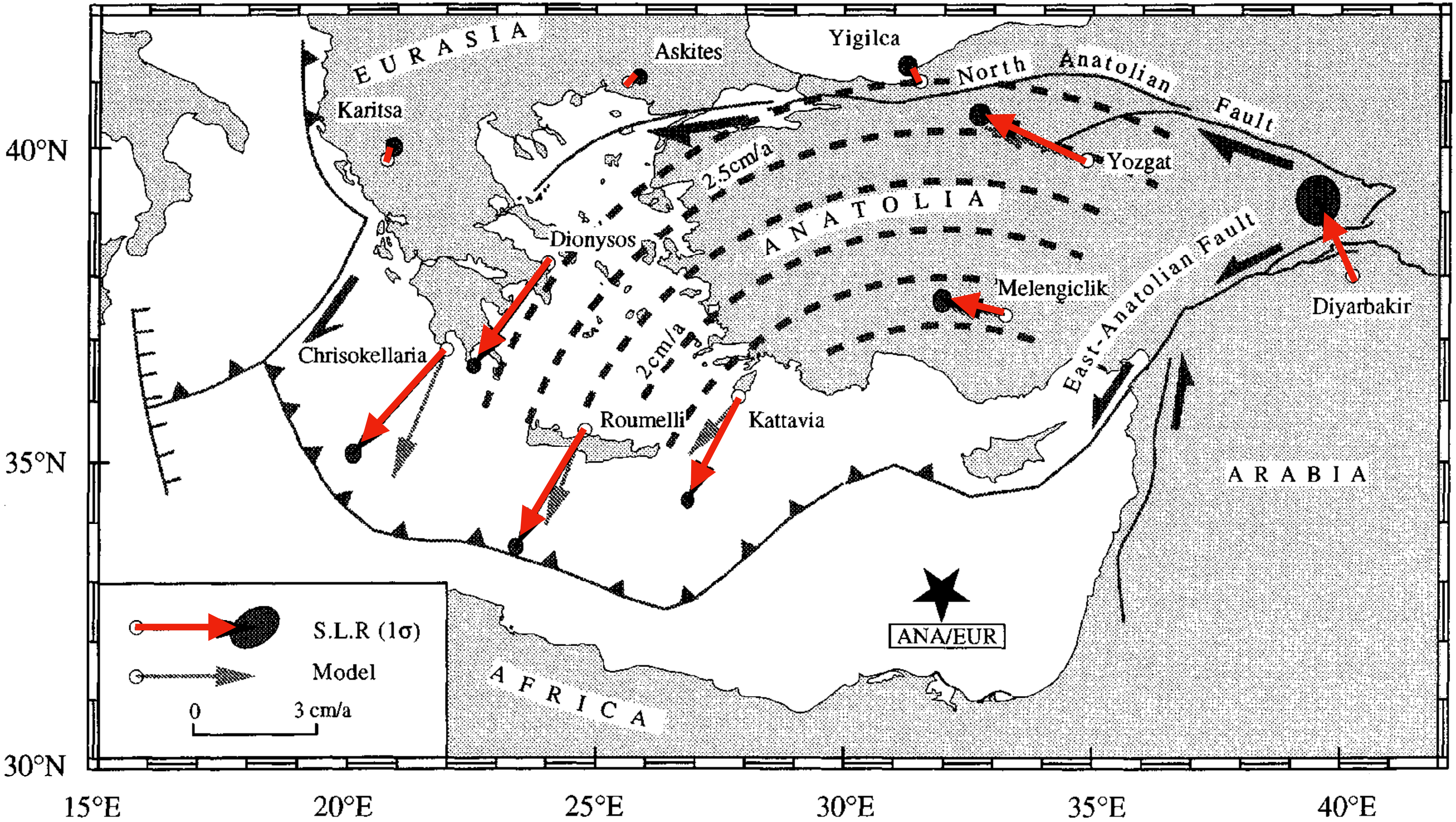
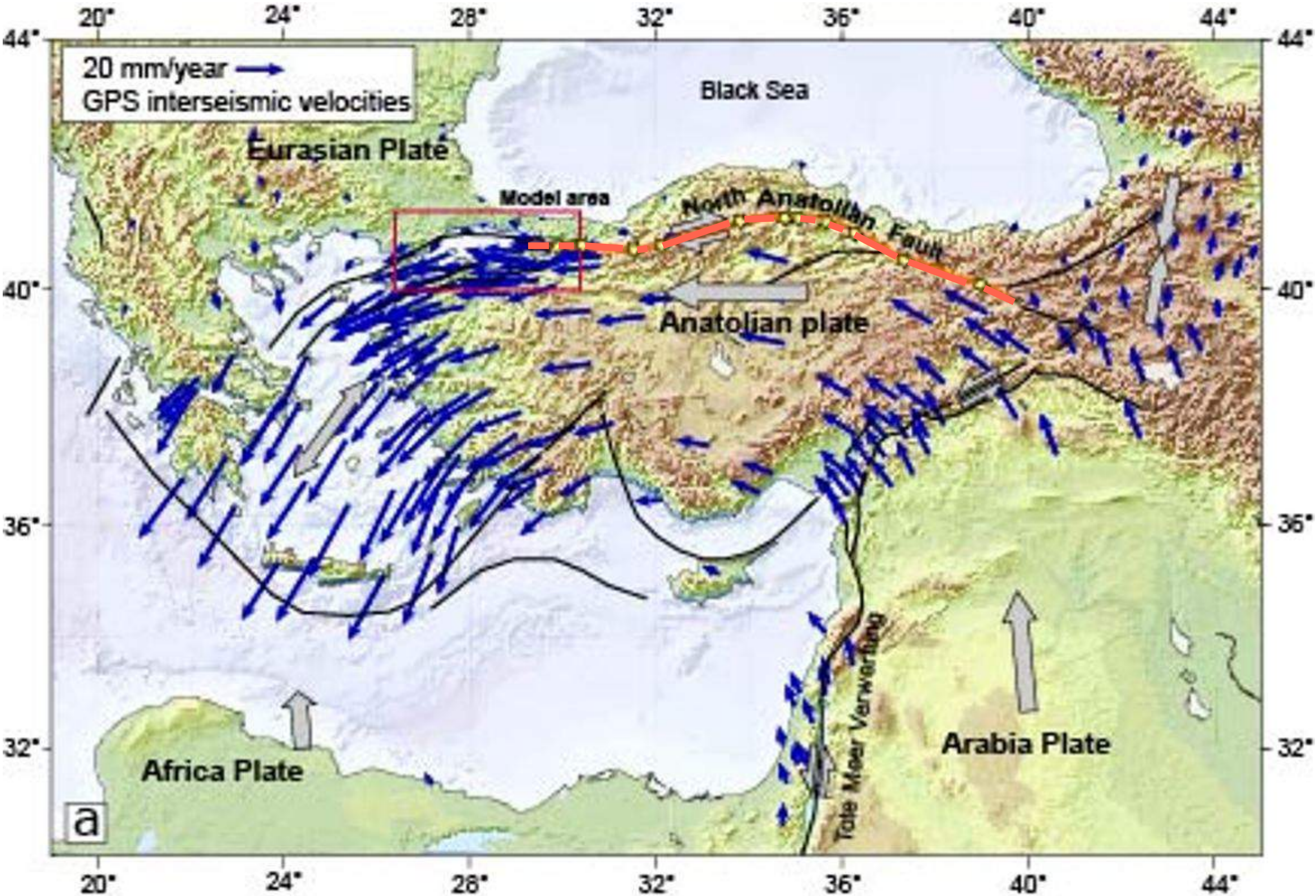


Figure 1. Solid arrows are SLR vectors with respect to Europe using the SSC[DUT]94C01 solution. Shaded arrows are computed vectors corresponding to the rigid rotation best fitting the Anatolian extrusion (see text). Star (ANA/EUR) locates the position of the pole of rotation. Dashed lines describe small circles corresponding to this rigid rotation. The edge of the Mediterranean Ridge accretionary wedge is identified as a solid line with triangles.


20 mm/year
GPS interseismic velocities
Black Sea
Eurasian Plate
Model area
North Anatolian Fault
Anatolian plate
Africa Plate
Arabia Plate
Tote Meer Verwerfung
a
20°
24°
28°
32°
36°
40°
44°
44°
40°
36°
32°

**P. Tapponnier, G. Peltzer,
A.Y. LeDain, R. Armijo, and
P. Cobbold**

Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine

Geology, v. 10 , Dec. 1982

The Problem: A strong ‘India’ pushes northward into ‘Asia’. *<u>If</u>* ‘Asia’ deforms ‘*<u>plastically</u>*’, that is not fluid-like but with distinct shear-zones/faults, a ‘Tibet’ that can’t move northward into a strong ‘Asia’, could move eastward toward an accommodating Pacific as a triangular wedge, first pushing Indochina and then South China out of its way.

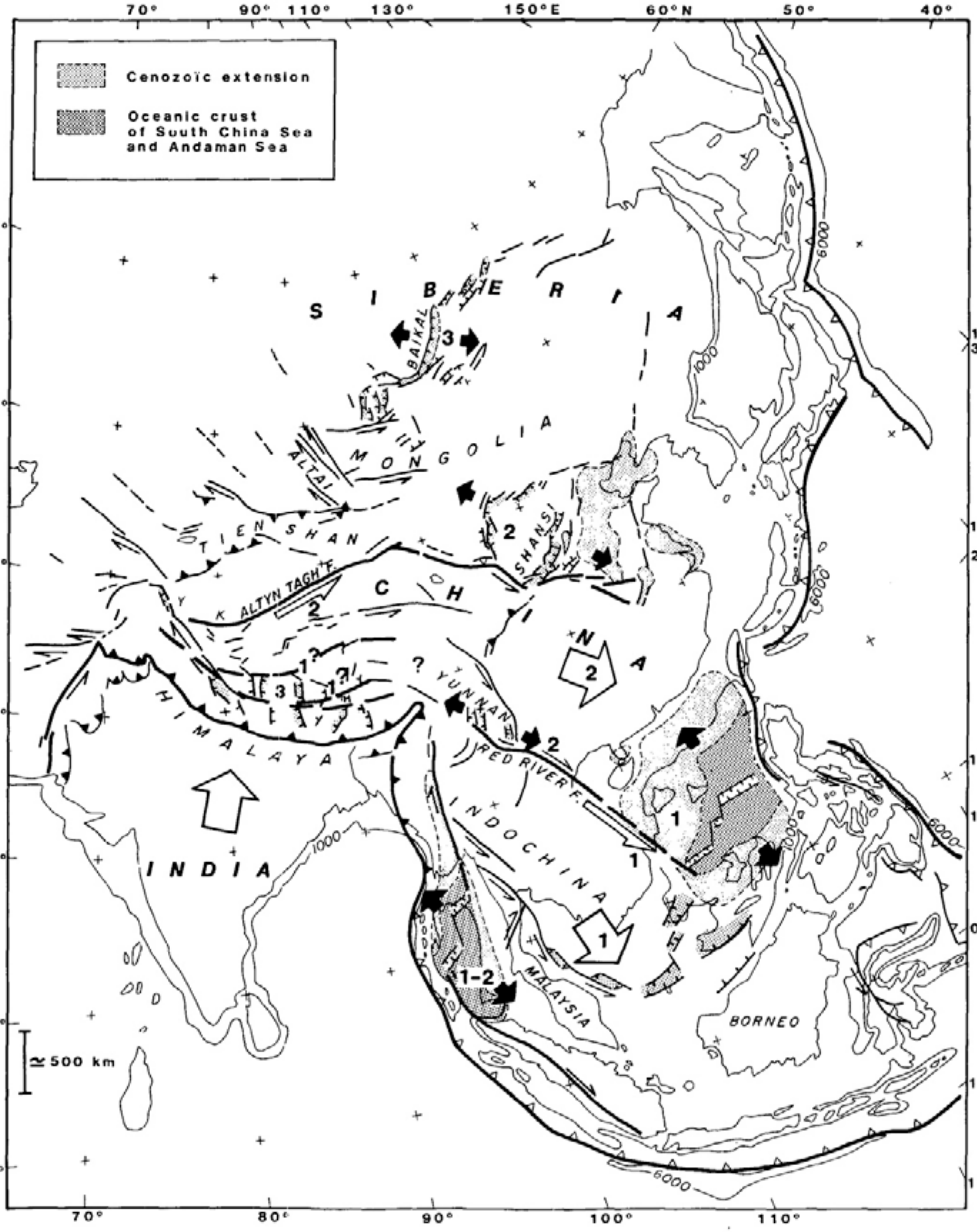


Figure 1. Schematic map of Cenozoic extrusion tectonics and large faults in eastern Asia. Heavy lines = major faults or plate boundaries; thin lines = less important faults. Open barbs indicate subduction; solid barbs indicate intracontinental thrusts. White arrows represent qualitatively major block motions with respect to Siberia (rotations are not represented). Black arrows indicate direction of extrusion-related extension. Numbers refer to extrusion phases: 1 ≈ 50 to 20 m.y. B.P.; 2 ≈ 20 to 0 m.y. B.P.; 3 = most recent and future. Arrows on faults in western Malaysia, Gulf of Thailand, and southwestern China Sea (earliest extrusion phase) do not correspond to present-day motions.

612 GEOLOGY, December 1982

The experiment

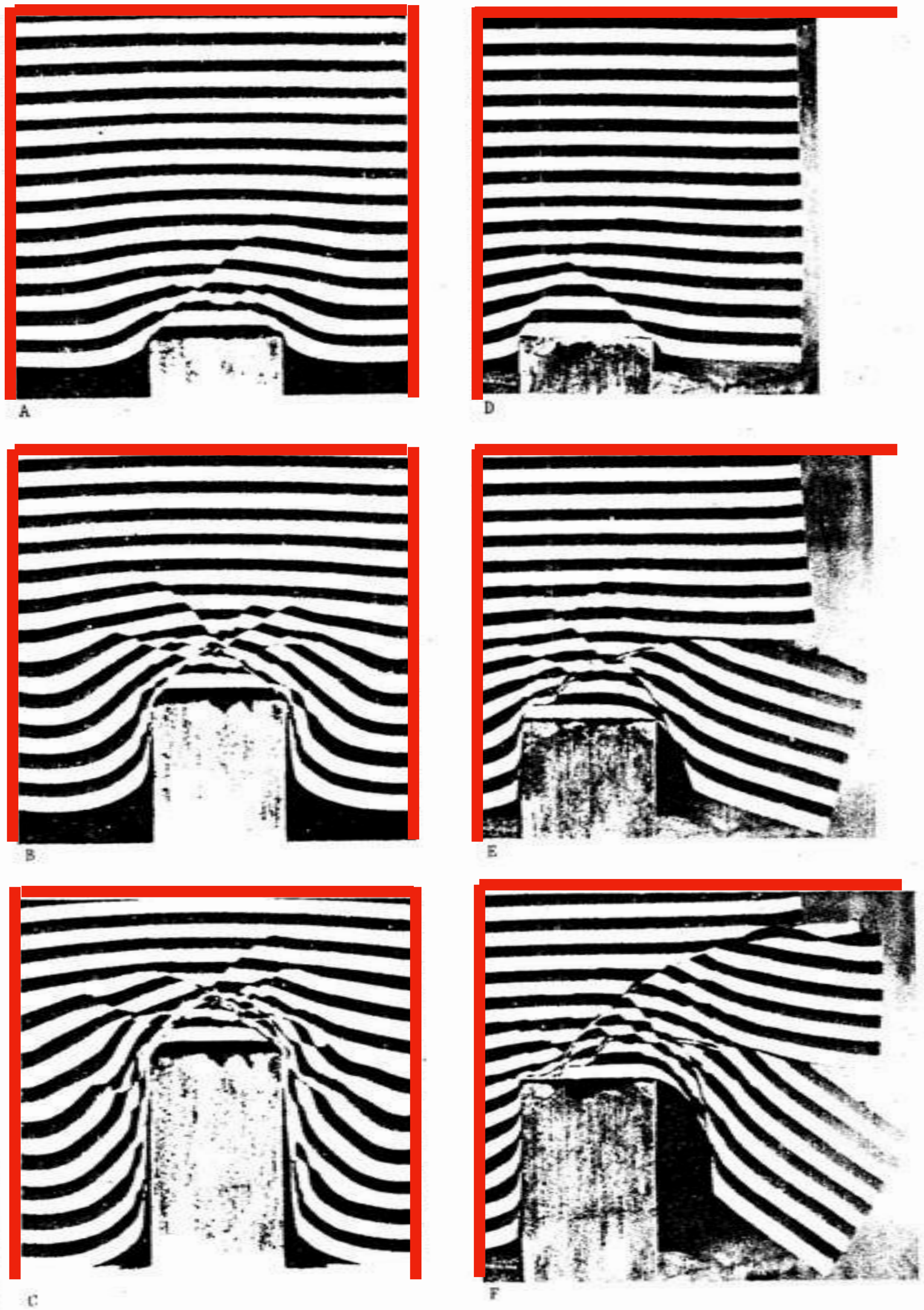


Figure 2. Three successive stages of two indentation experiments on plasticine. A, B, C: bilaterally confined; D, E, F: unilaterally confined (free side on right). Indenter displacements for A and D = 1.2 cm; for B and E = 3.5 cm; for C and F = 6.3 cm. Note narrow shear zones or faults, and open gaps on right side in E and F (after Peltzer and others, 1982).

Interpretation

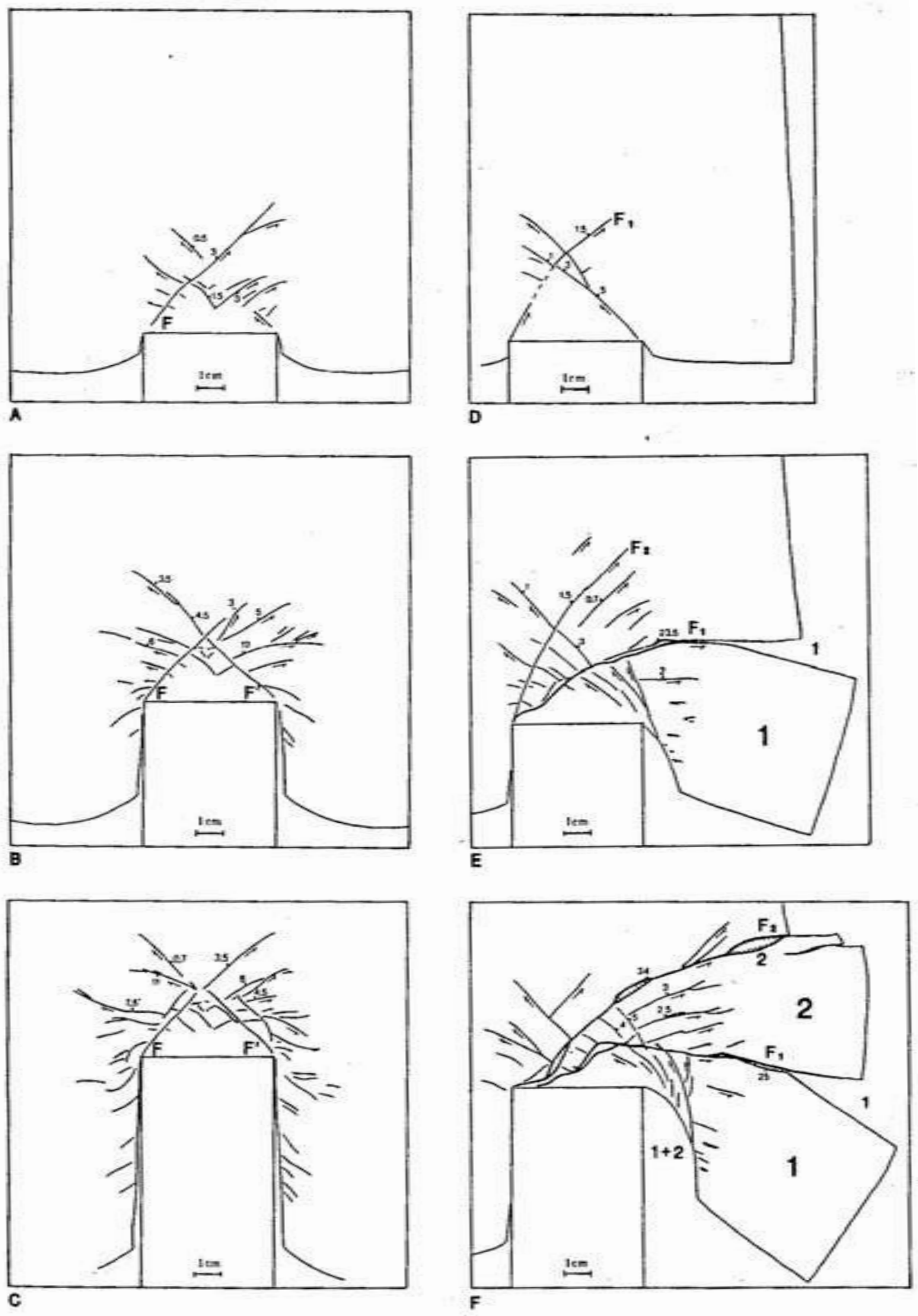
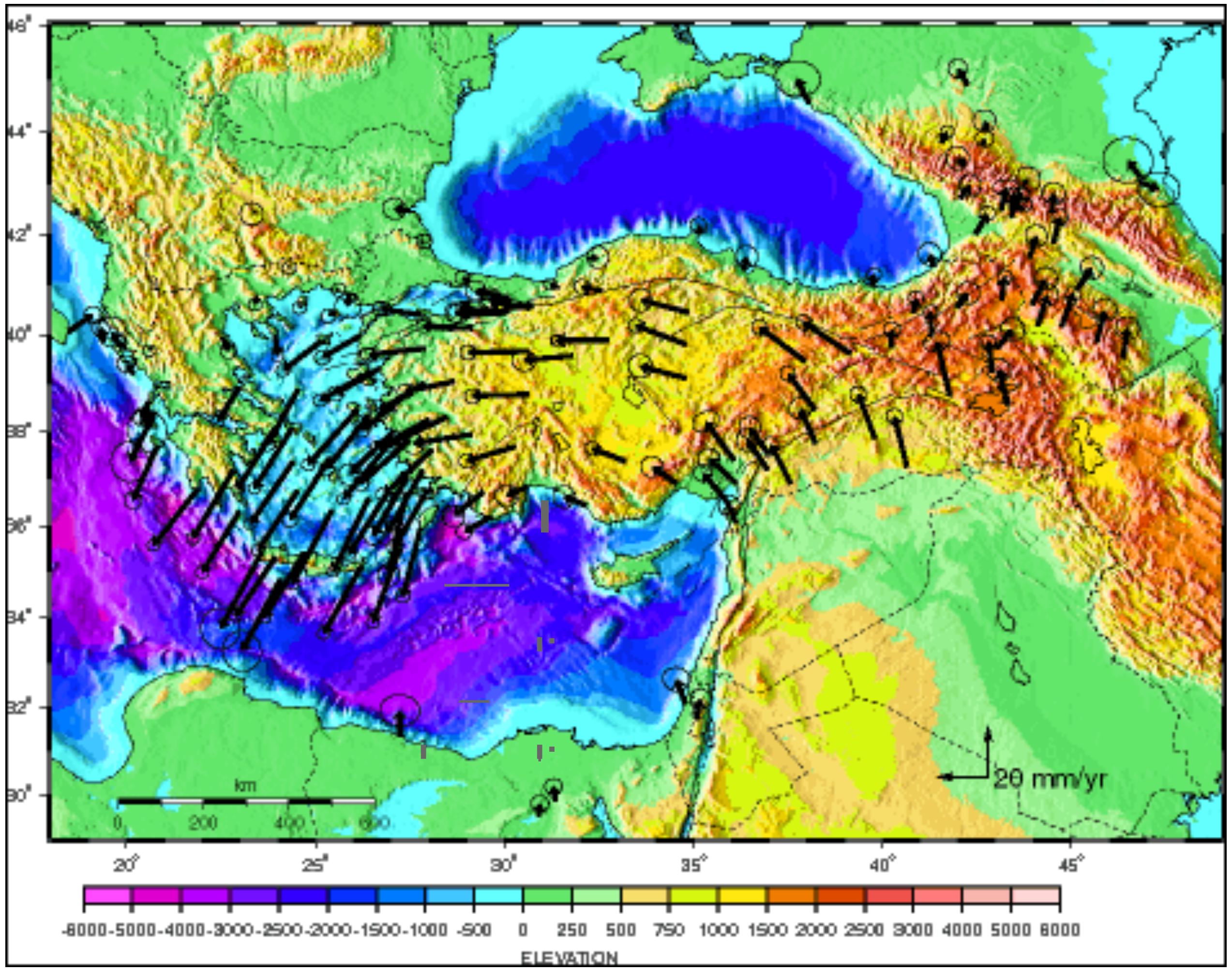


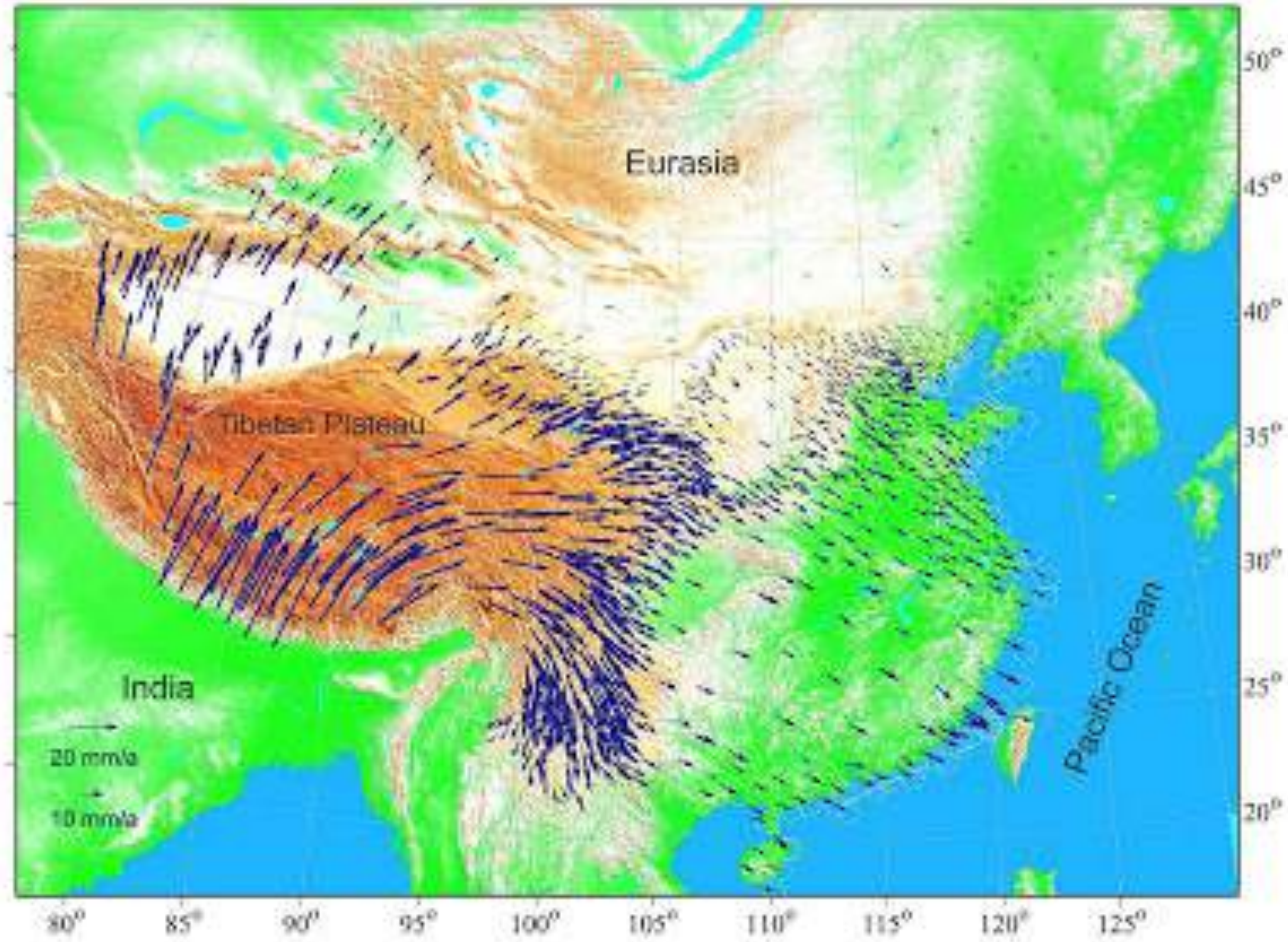
Figure 3. Hand drawings of faults observed in experiments of Figure 2, with cumulative offsets in millimetres (small numbers) (after Peltzer and others, 1982). In unilaterally confined experiment, two major faults (F1 and F2) guide successive extrusion of two blocks. In stage F, blocks 1 and 2 can be compared to Indochina and southern China, and open gaps 1, 1 + 2, and 2 to South China Sea, Andaman Sea, and northeastern China, respectively.

(Tapponnier *et al*.,1982)

Note the narrow shear zones (faults) form one-at-a-time.

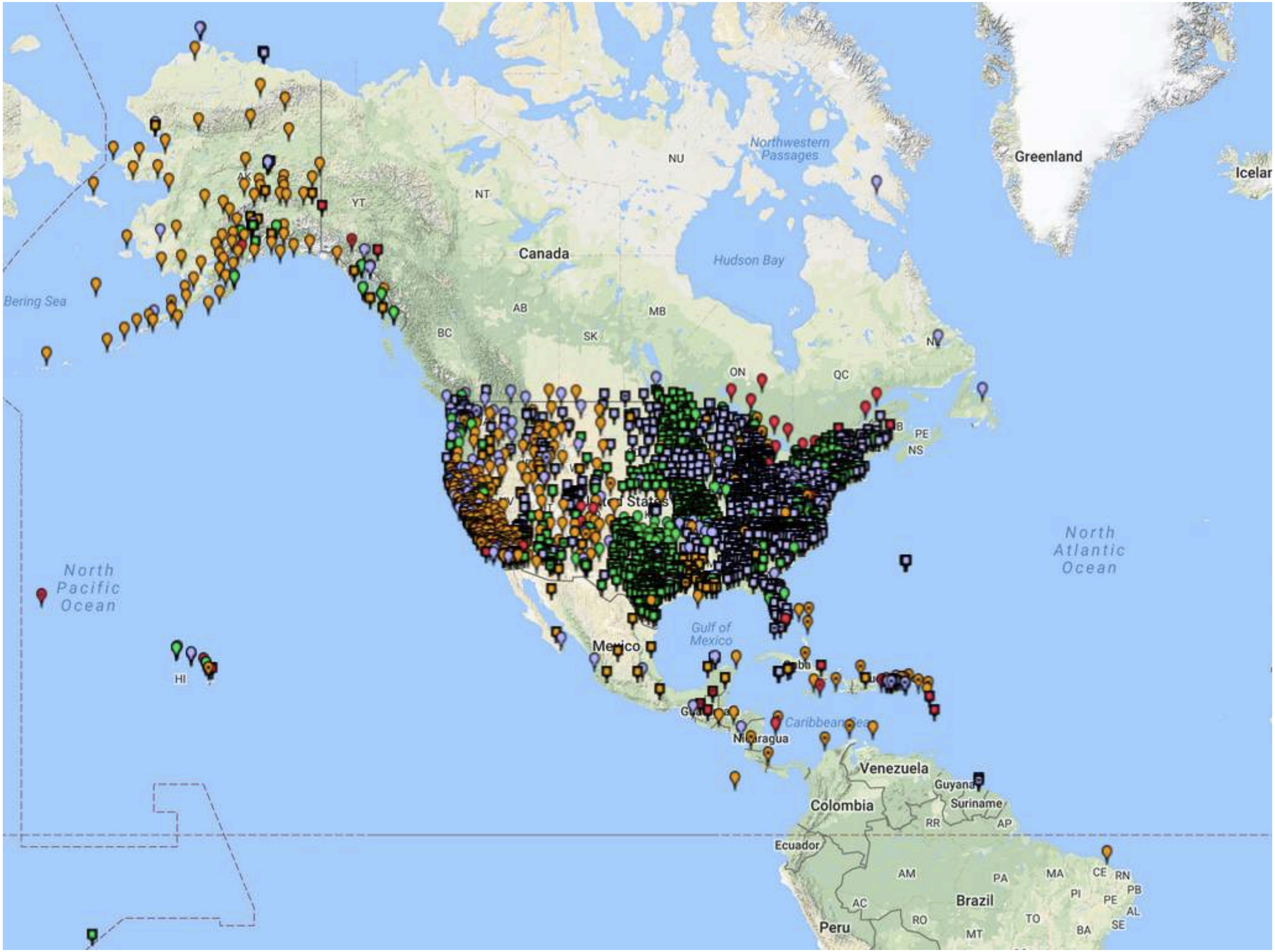
GPS - now can measure positions with an accuracy of ~ 1 mm. This new tool should do for continental tectonics what magnetic anomalies did for oceanic tectonics.





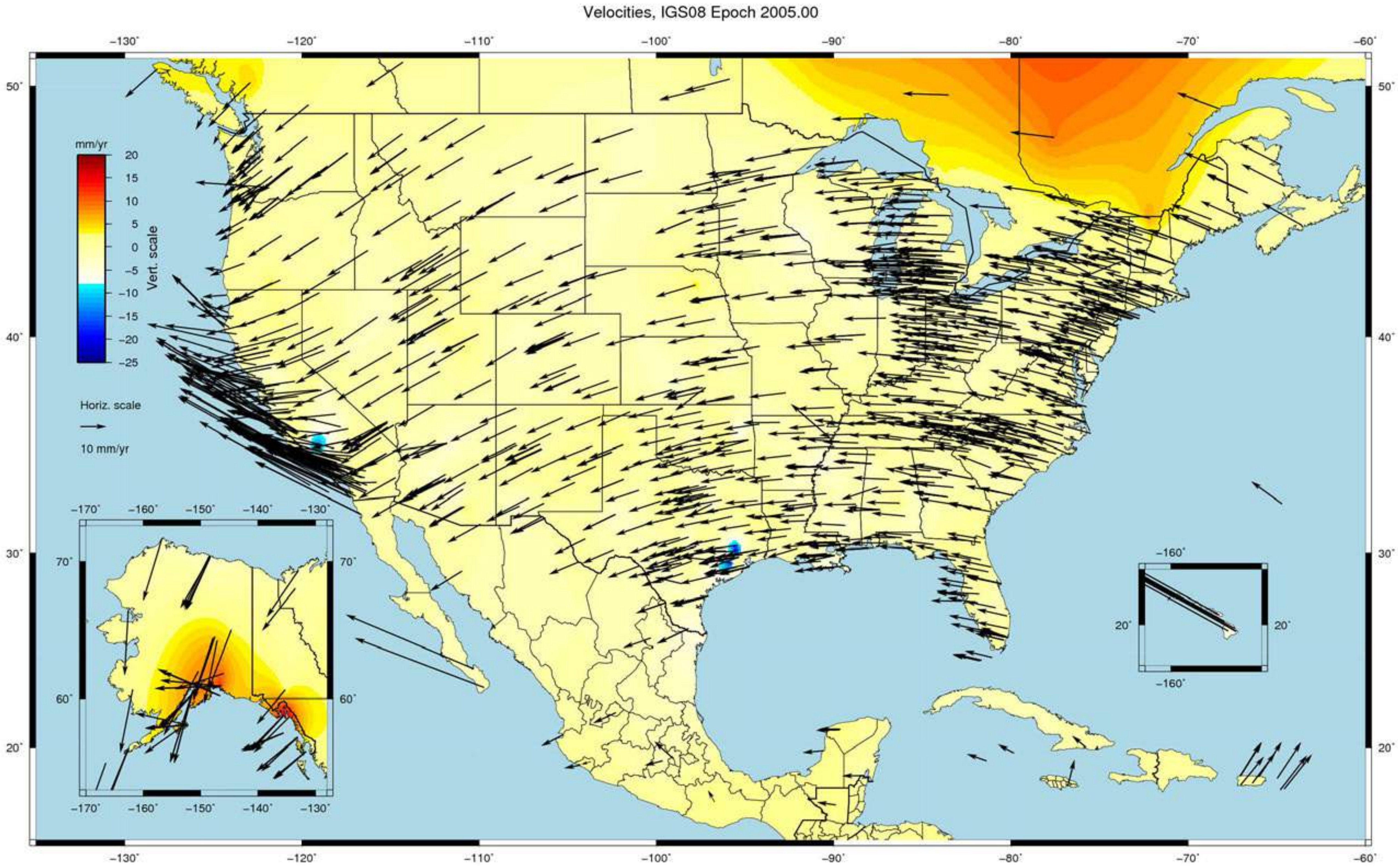
Map showing density of GPS stations operating in U.S.

(2017)



GPS velocities with respect to Global Reference Frame (IGS08)

(In the next slide, a single rotation that best-fits the more stable part of North America will be subtracted-out to emphasize the non-rigid distortion.)



What the dense GPS network in Eastern U.S. will be able to study: the present-day vertical and horizontal adjustments following the melting of the ice-age glacier.

SELLA ET AL.: OBSERVATION OF GLACIAL ISOSTATIC ADJUSTMENT **(GEOPHYS. RES. LETT., 2007)**

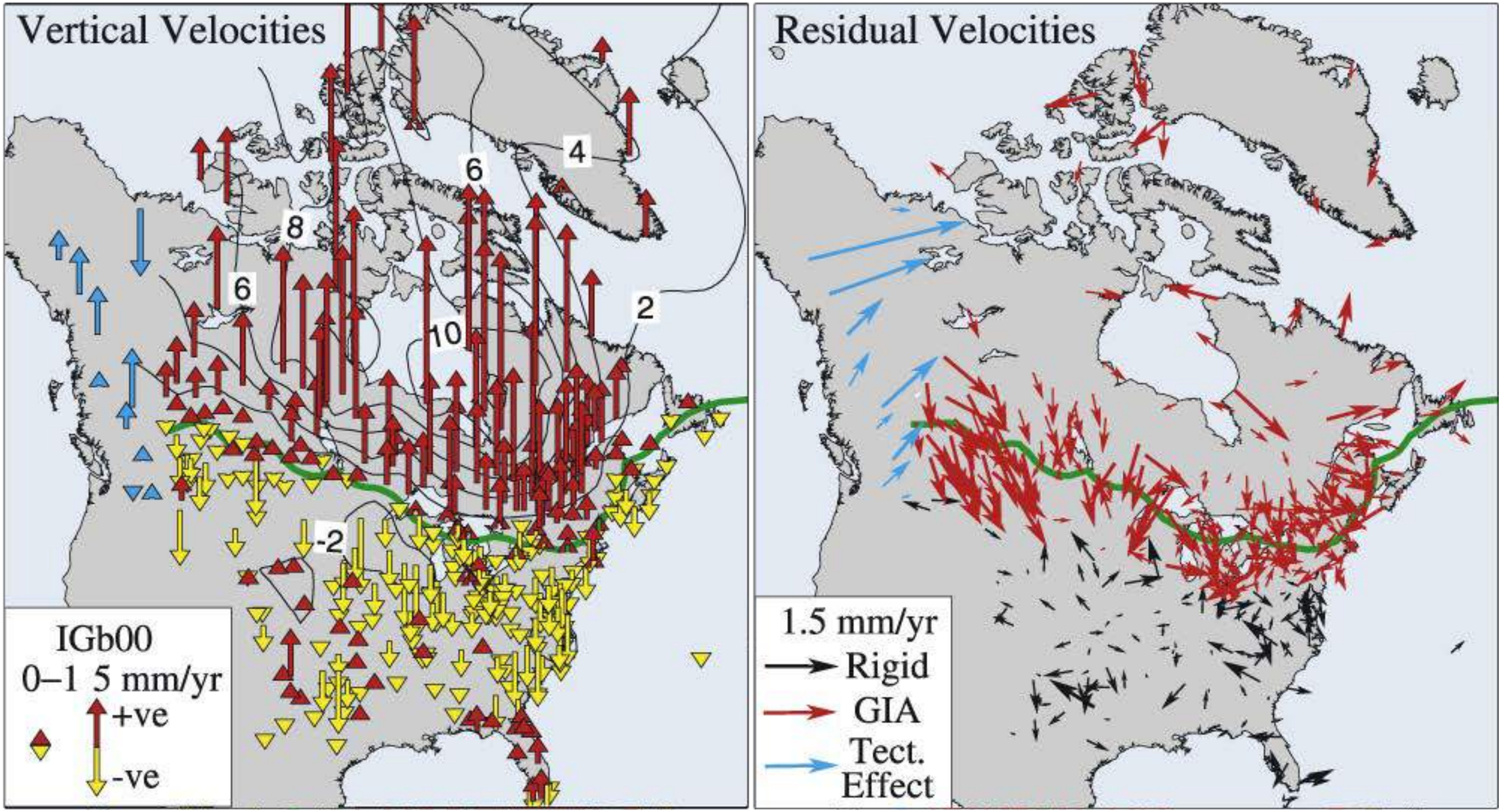
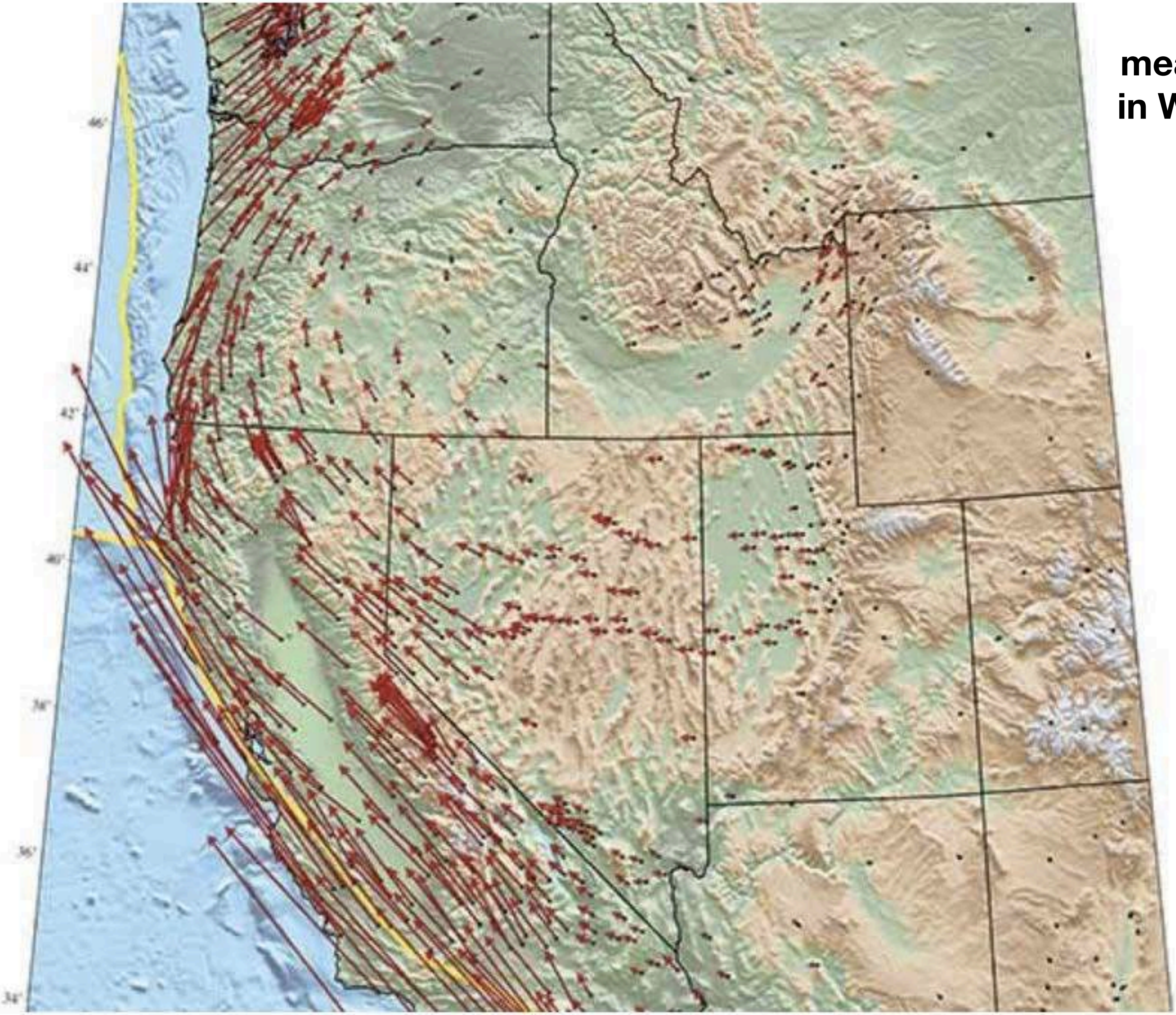


Figure 1. (left) Vertical GPS site motions with respect to IGb00. Note large uplift rates around Hudson Bay, and subsidence to the south. Green line shows interpolated 0 mm/yr vertical "hinge line" separating uplift from subsidence. (right) Horizontal motion site residuals after subtracting best fit rigid plate rotation model defined by sites shown with black arrows. Red vectors represent sites primarily affected by GIA. Purple vectors represent sites that include effects of tectonics.

GPS measurements in Western U.S.



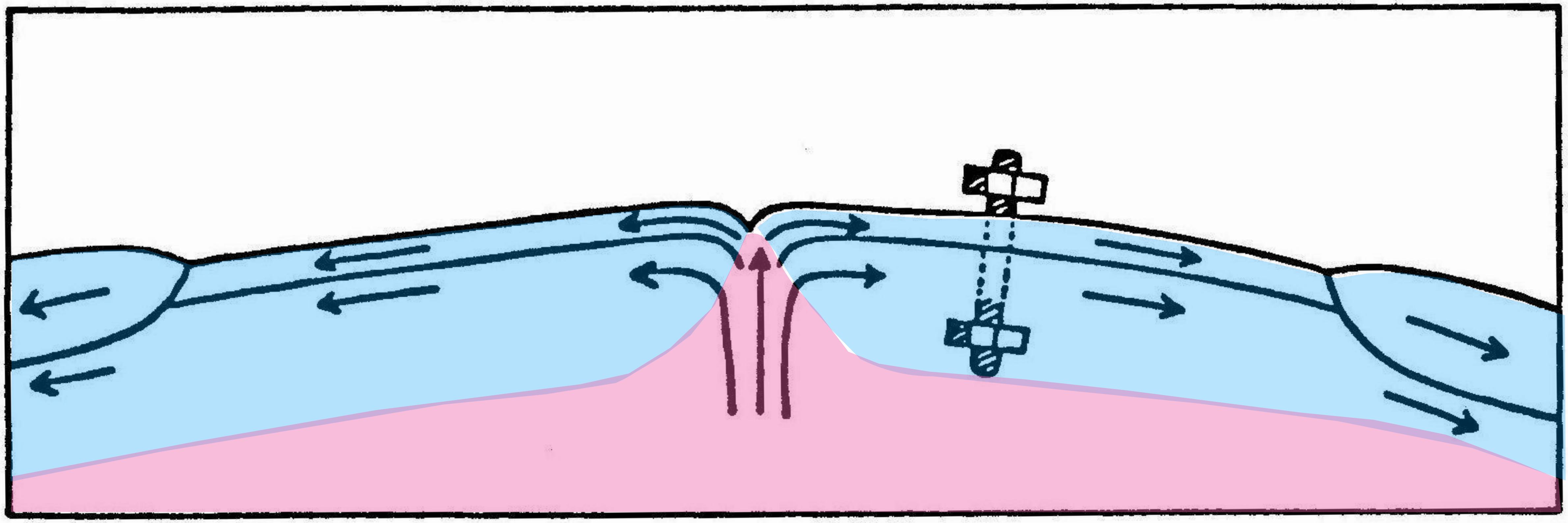
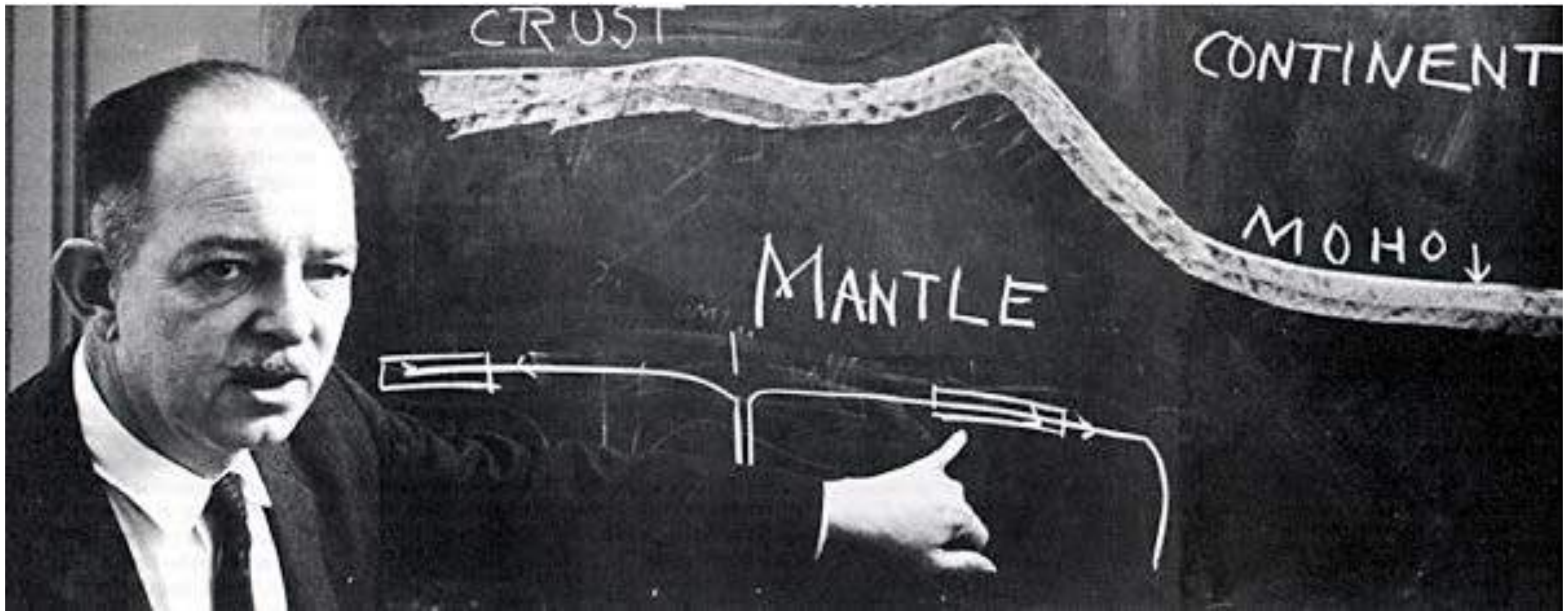


Figure 123. The crust and mantle move laterally away from the ridge-axis, both moving at the same velocity so there is no viscous drag effect. The trailing edges of continents are not deformed. The crust and mantle may be considered effectively to be bolted together. The continents move passively until their leading edges arrive at the site of the downward current. **(H. H. Hess)**



“A more acceptable mechanism is derived for continental drift whereby continents ride passively on convecting mantle instead of having to plow through oceanic crust.” (Hess, 1960)

Hess's original idea is still true, the earth has a very strong outer layer (the lithosphere, ~100+ km thick) upon which both continental crust and ocean floor move over a weak, more fluid-like material (the asthenosphere).

The idealization of 'perfectly rigid plates' was just a mathematical convenience to allow calculations (predictions) of surface motions. Velocities <u>once</u> could be measured <u>only</u> at mid-ocean ridges (with magnetic anomalies) and a method to transfer these velocities to continental regions was needed.

But now that motions can be directly <u>measured</u> (with GPS, *etc.*), <u>predictions are no longer needed</u> and the <u>assumption of 'perfect rigidity' is no longer needed</u>.