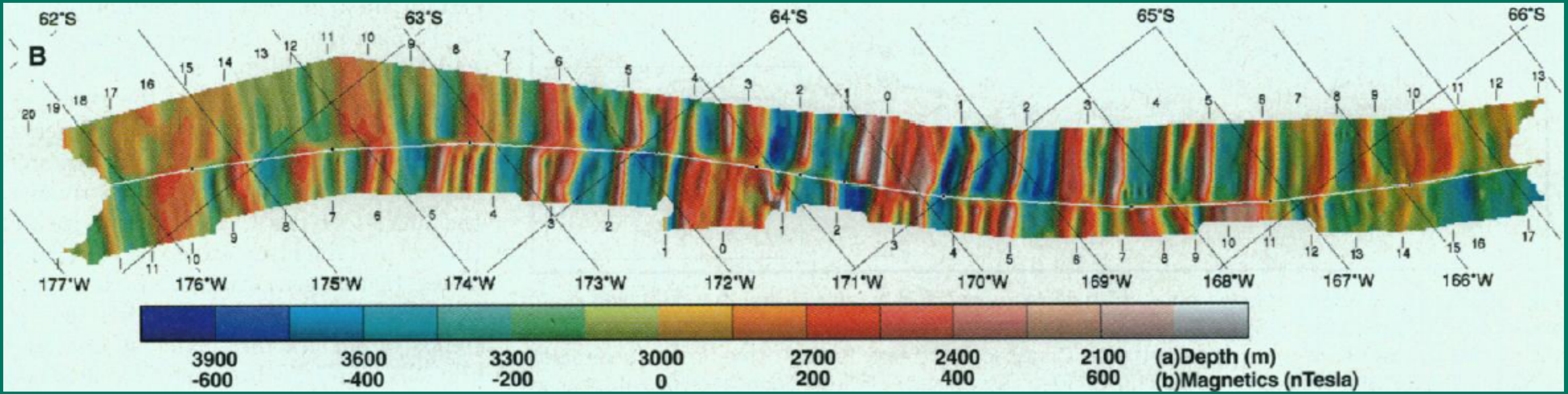
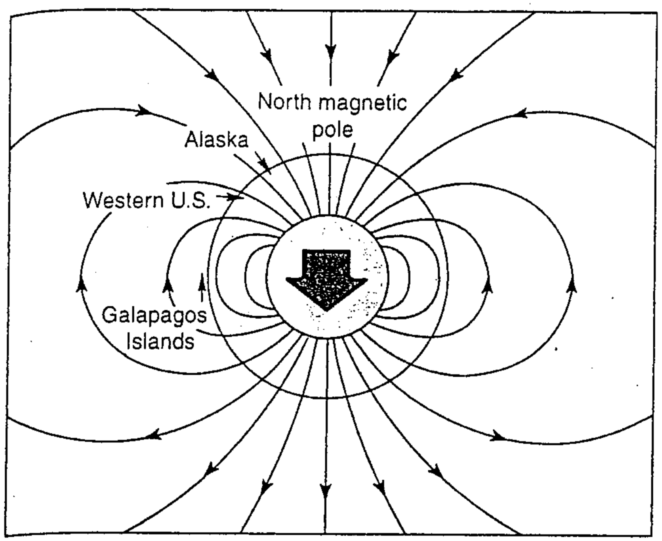
# Magnetic Anomalies and Seafloor Spreading

read chapter 4.1 of KK&V



EARTH'S MAGNETIC FIELD



(A) Normal polarity

Hamblin and Christiansen (2001)

To first order, Earth's magnetic field is a dipole.

The strength of the field varies between, roughly
25,000 nT (near the equator) and
65,000 nT (near the poles). nT = nanoTesla

The Main (Core) Field is generated in the outer (liquid) core by a "geodynamo."

Rocks in the crust acquire magnetizations by various processes.
E.g. when rocks cool through the Curie isotherm they may acquire a Thermal Remanent Magnetization (TRM).

Anomalies due to crustal sources are small: 20 to 1000 nT

The mantle is essentially non-magnetic.

Total field = Core Field + Crustal Anomalies
(99%) (~1%)

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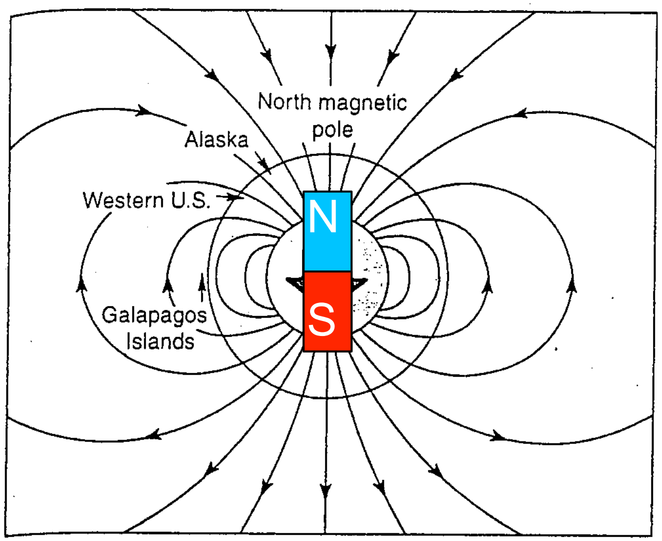


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Averaged over periods of time greater than about 5 kyr the geomagnetic field is a dipole aligned with the Earth' spin axis.

## Geocentric Axial Dipole (GAD) hypothesis

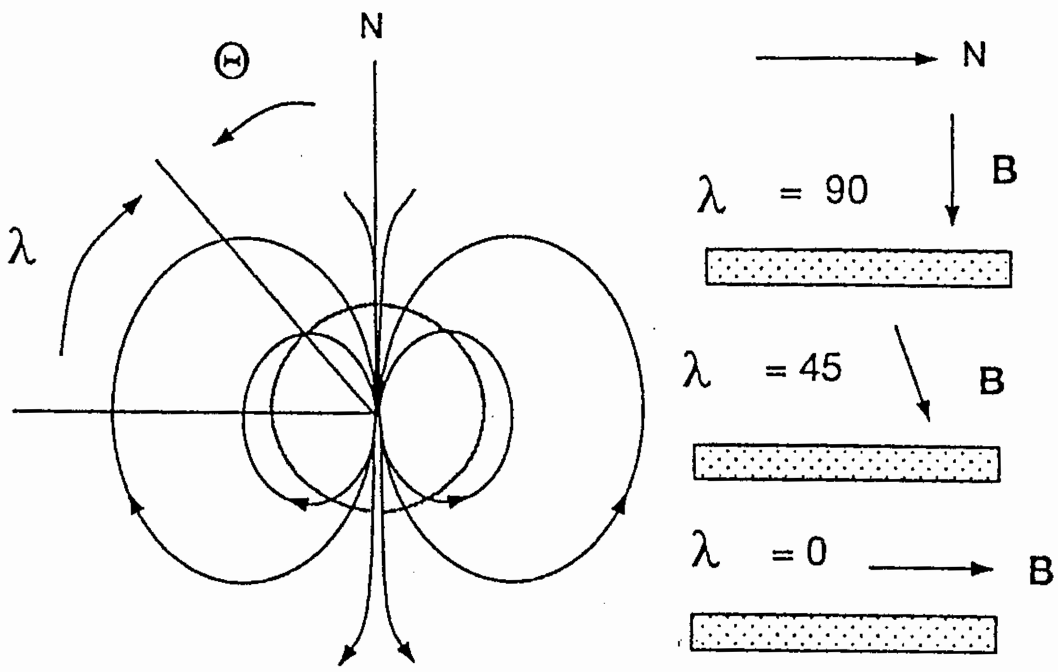



*Figure 1.4.* Geocentric dipole field. $\lambda$ and $\theta$ are latitude and co-latitude respectively. To the right: inclinations of magnetic field B relative to the Earth's surface at various latitudes.

# International Geomagnetic Reference Field (IGRF)

The long wavelength variations of the magnetic field (caused by the main core field) are quantitatively described by a set of spherical harmonic coefficients. These coefficients describe the shape of the field from the longest wavelengths (the dipole term) down to wavelengths as short as, roughly, 3000 km (e.g. degree and order 10). These coefficients are updated every 5 years.

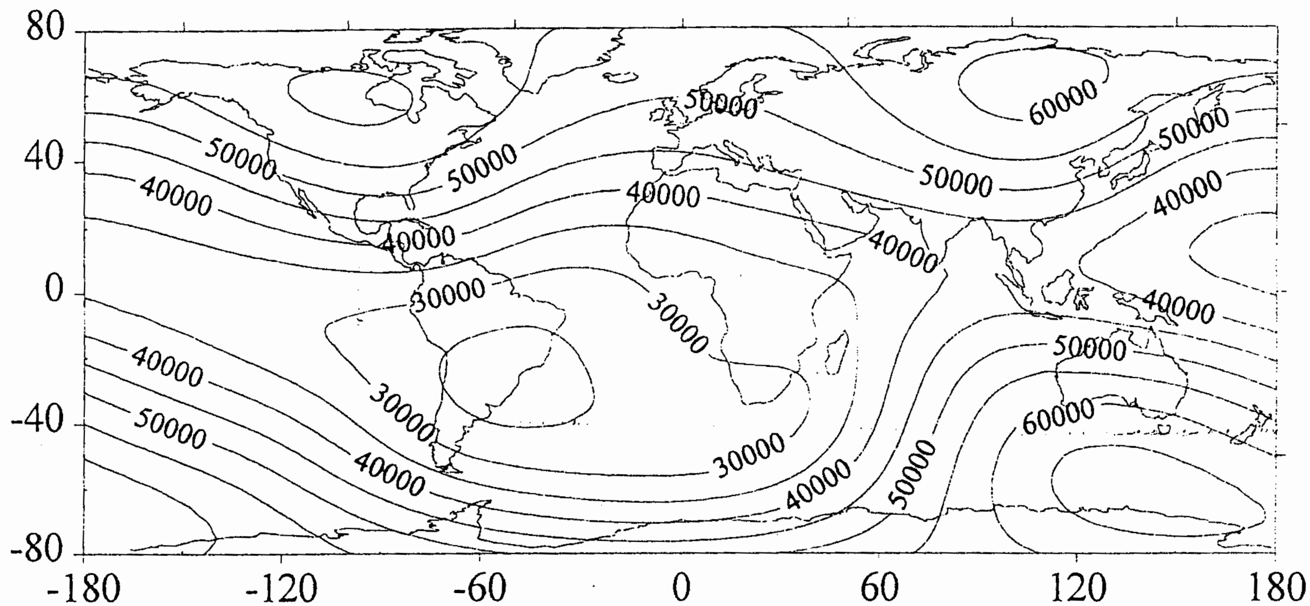
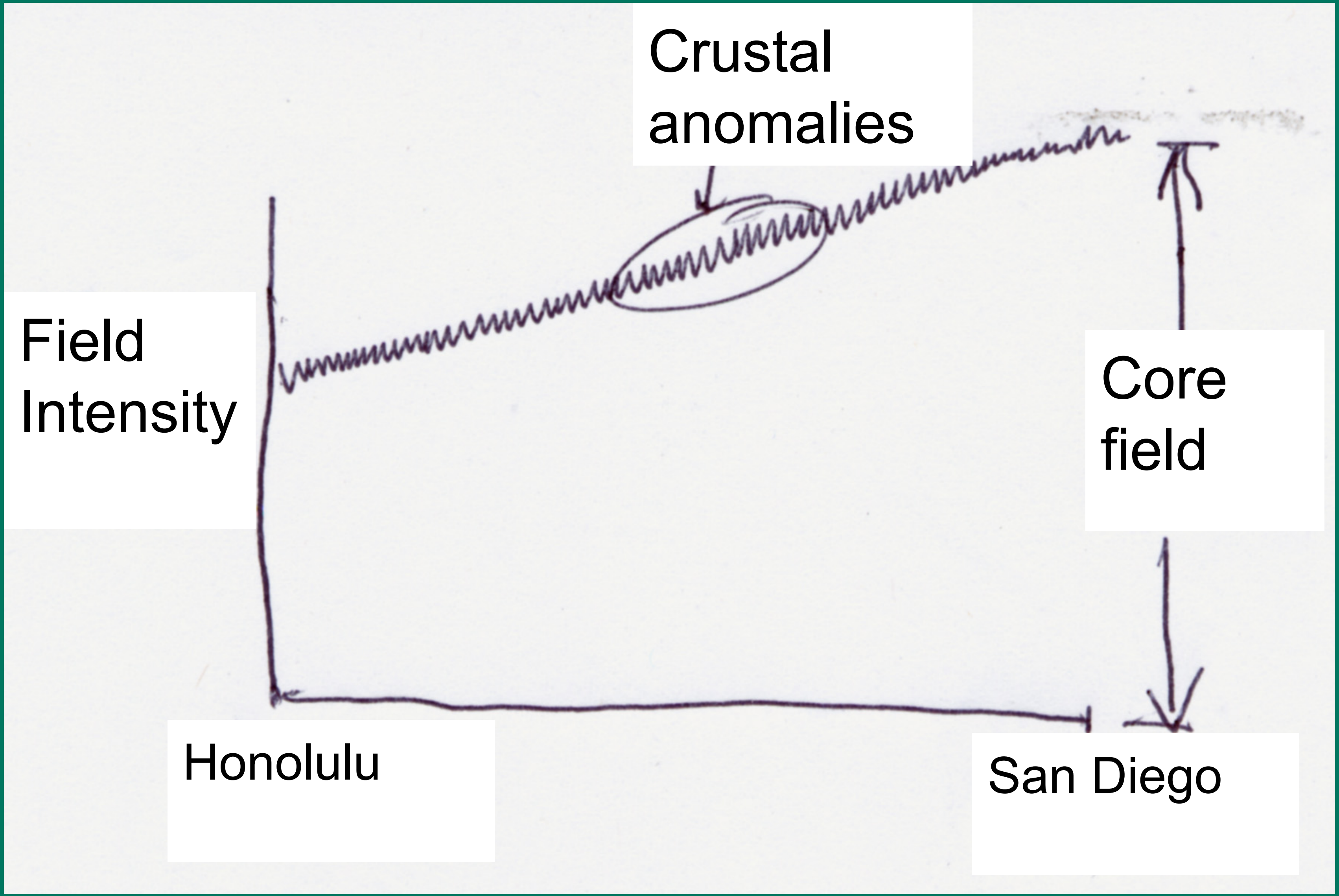



**Fig. 2.3c.** Isodynamic chart for 1990 showing the variation of total intensity over the Earth's surface. Contours are labeled in nT.

Merrill et al. (1996)

Magnetic anomalies are the leftovers after you subtract the regional (core) field.

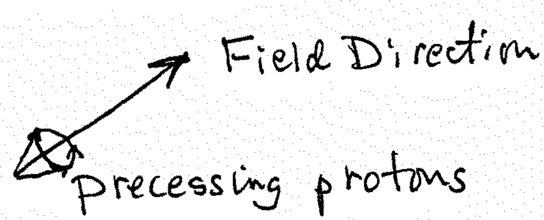


# Measuring the Magnetic Field at Sea

The TOTAL field strength can be measured with a Proton Precession Magnetometer

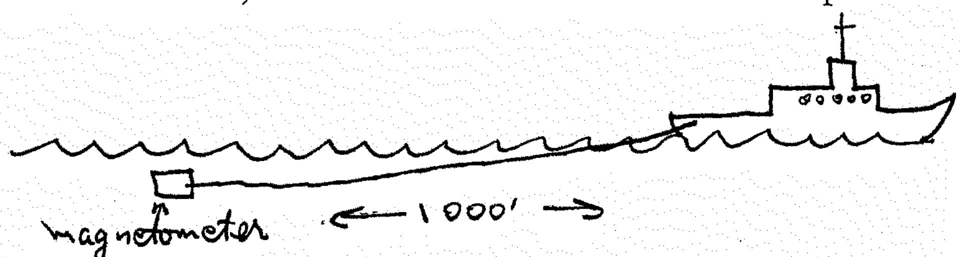
Principle:

Free protons precess about a magnetic field at a frequency proportional to the field strength



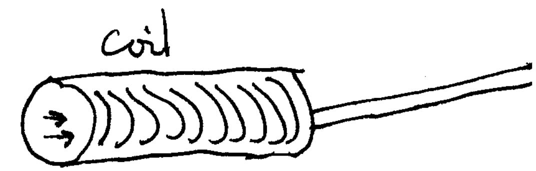

In practice:

A small coil is filled with a fluid containing free protons (e.g.distilled water or benzene) and towed about 1000 feet behind a ship.

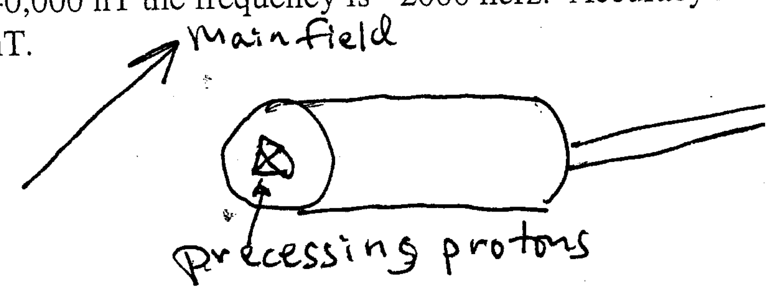



Two step process

1) Polarize coil for 1 or 2 seconds; protons line up parallel to long axis of coil




2) Stop polarizing; protons precess as they line up parallel to Earth's field. Measure frequency of precession for ~1 sec. For a field strength of ~40,000 nT the frequency is ~2000 herz. Accuracy is about 1 or 2 nT.



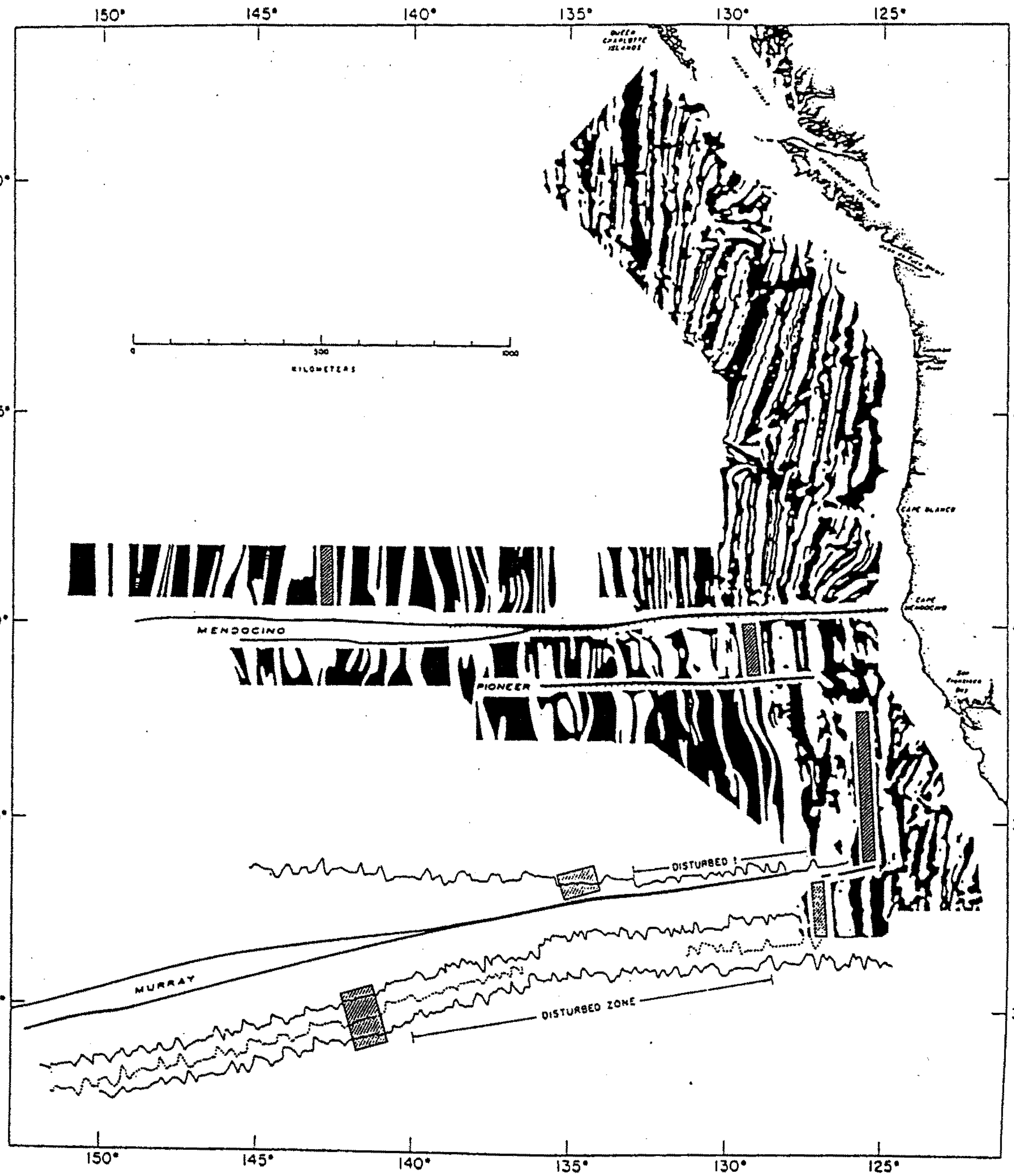



*Figure 3.4* Magnetic anomalies and offsets on fracture zones.

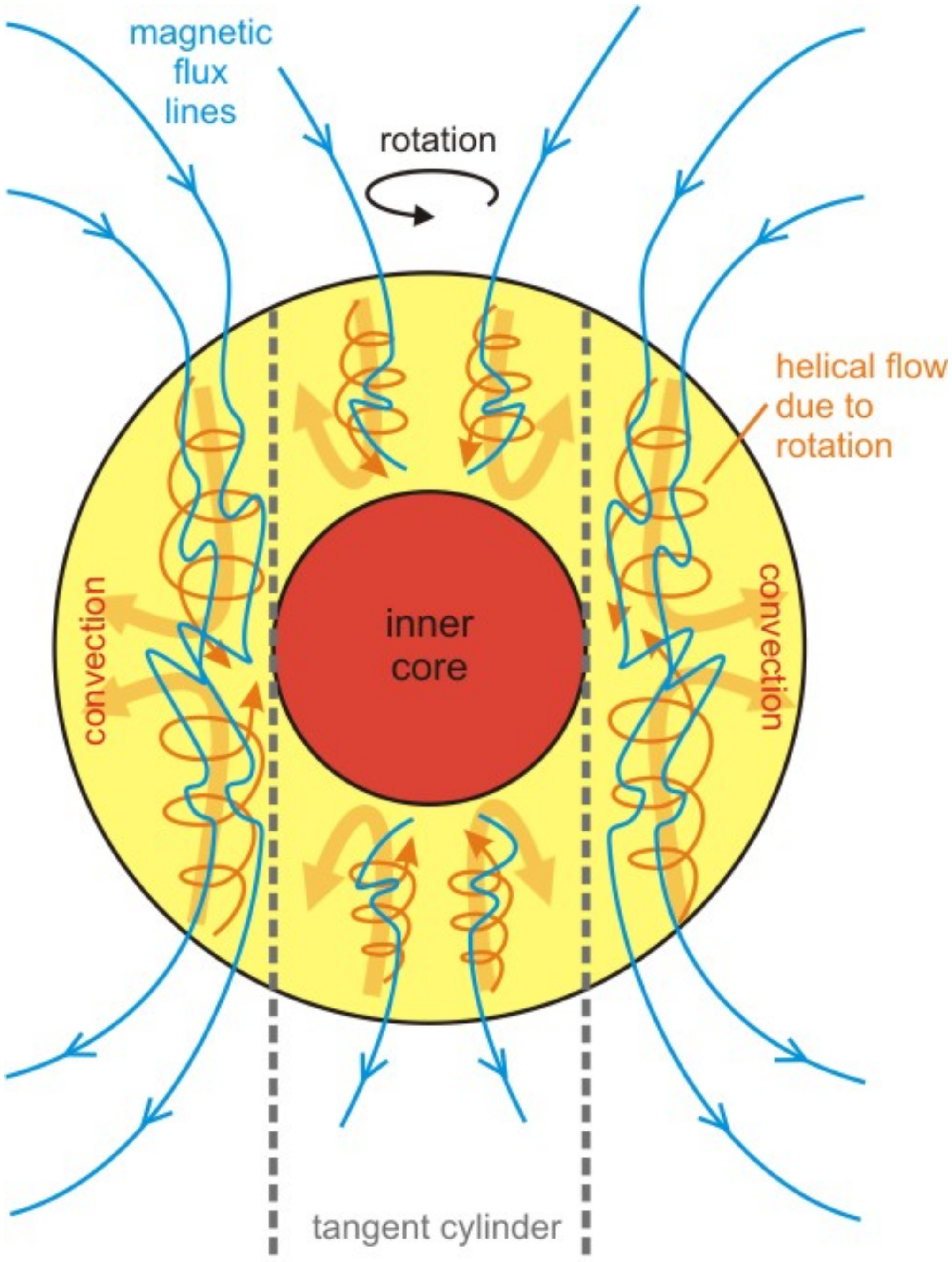
MENARD(1964)

Surveys of magnetic field off of west coast in mid-1950's by Raff and Mason discovered linear magnetic anomalies: "zebra stripes."

Their origin was a mystery.

Unfortunately for Raff and Mason, this was before it was known that the magnetic field reverses periodically.

# How and why does the magnetic field reverse?



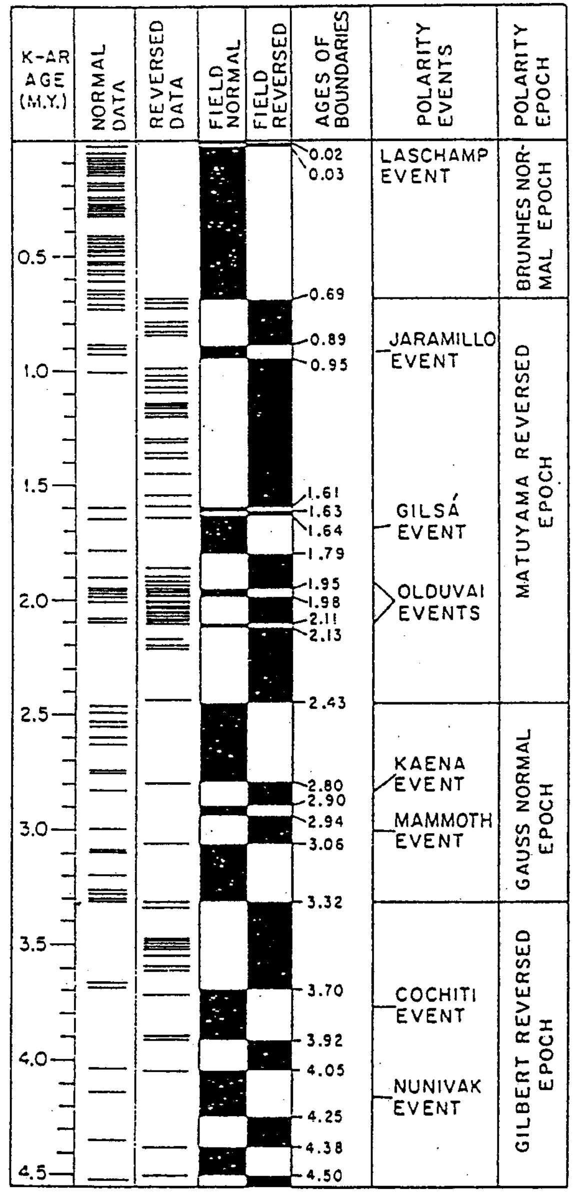

Geodynamo – self-sustained generation of magnetic field due to convective motion of conductive material (iron) in the outer core

The polarity of magnetic field can change spontaneously (reproduced in models – G. Glatzmeier)

Such reversals are usually preceded by a decrease in the field intensity

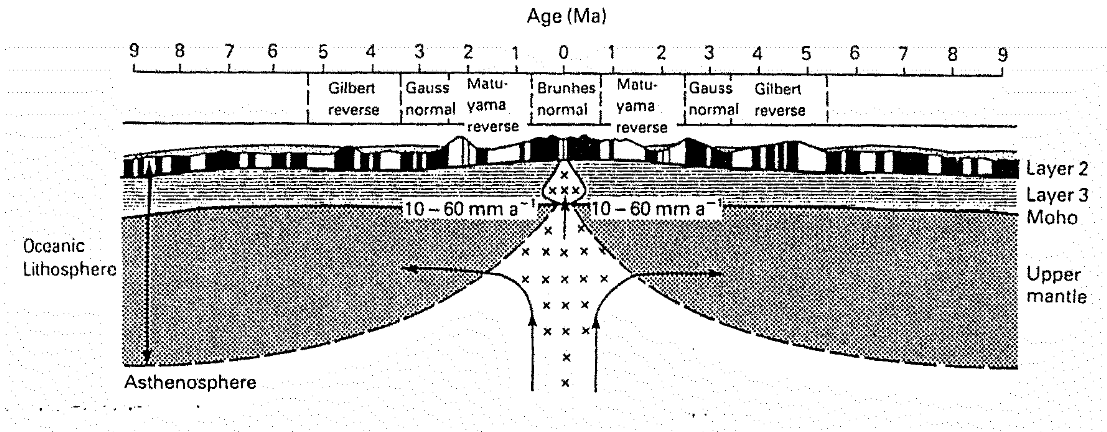
# How and why does the magnetic field reverse?

The classic geomagnetic polarity timescale determined by radiometric dating of volcanic rocks




Cox (1969)

5 Ma is about the limit for constraining the timescale by K/Ar dating of volcanic rocks.




Vine and Matthews hypothesis

Linear marine magnetic anomalies are a record of reversals of the earth's magnetic field that are "frozen in" at the ridge axis as the sea floor is spreading.

As the ocean floor spreads apart, hot basaltic magma is erupted at the mid-ocean ridges. When the magma cools below the Curie point, the direction of the ambient magnetic field is locked in the basalts. Because the magnetic field reverses polarity every few hundred thousand years, the anomalies form a distinctive pattern of highs and lows.

Over time, the magnetic anomalies form a symmetrical record (a giant dual-headed tape recorder) preserving the history of seafloor spreading and a history of the magnetic polarity of the magnetic field.

based on crummy data

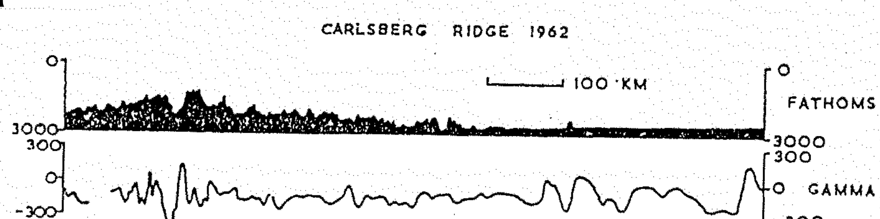
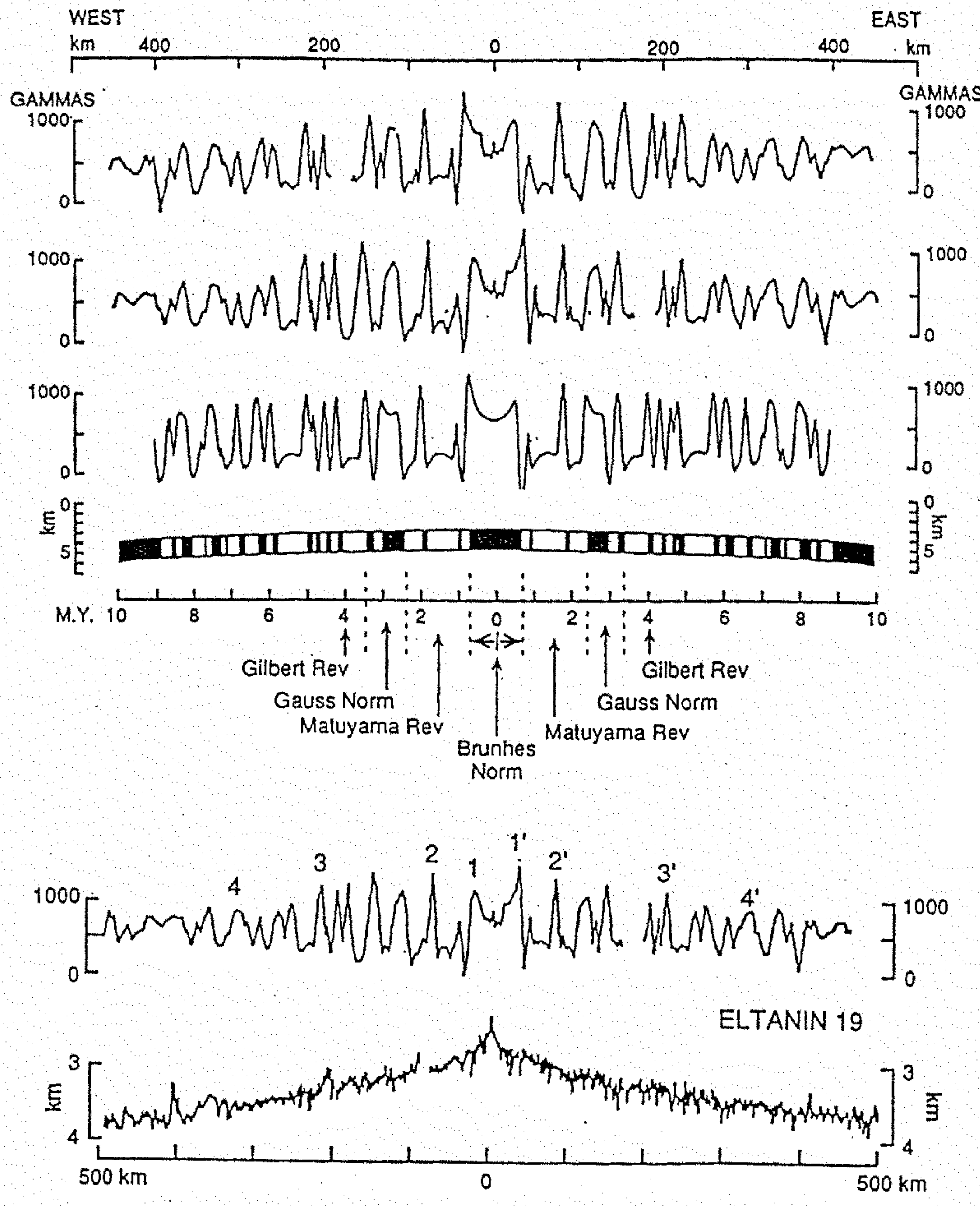



Fig. 1. Profiles showing bathymetry and the associated total magnetic field anomaly observed on crossing the North Atlantic and the north-west Indian Oceans. Upper profile from 45° 17′ N, 28° 27′ W. to 45° 19′ N, 11° 29′ W. Lower profile from 30° 5′ N, 61° 57′ E. to 10° 10′ N, 66° 27′ E.

Vine and Matthews (1963)

Eltanin 19 profile




The details came in 1966

Great data from the Pac-Ant ridge

Real character in the anomalies (3 fingers Brown)

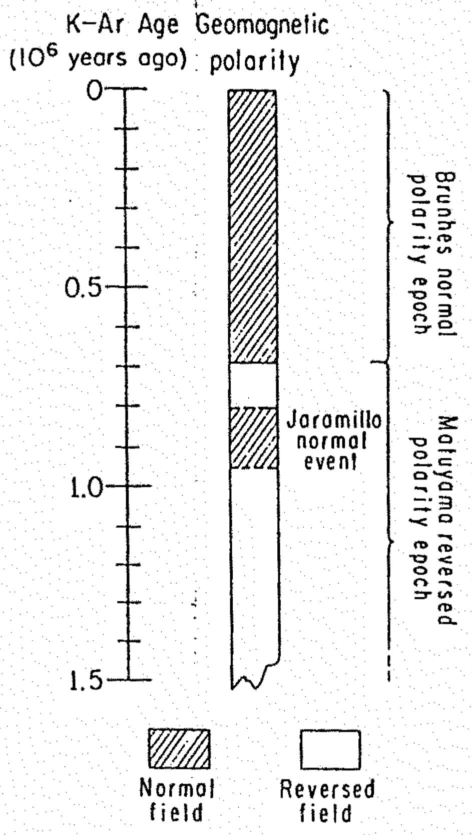
Expanded timescale to 10 Ma

Pitman & Heirtzler (1966)

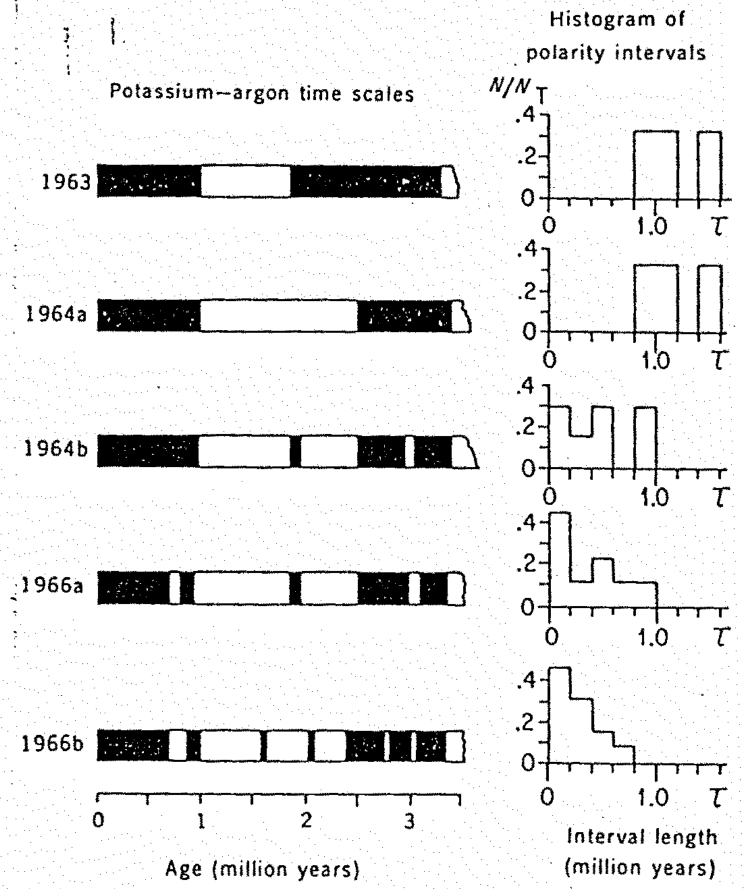
Doell and Dalrymple (1966)

Cox (1969)

The Jaramillo Short Polarity Event

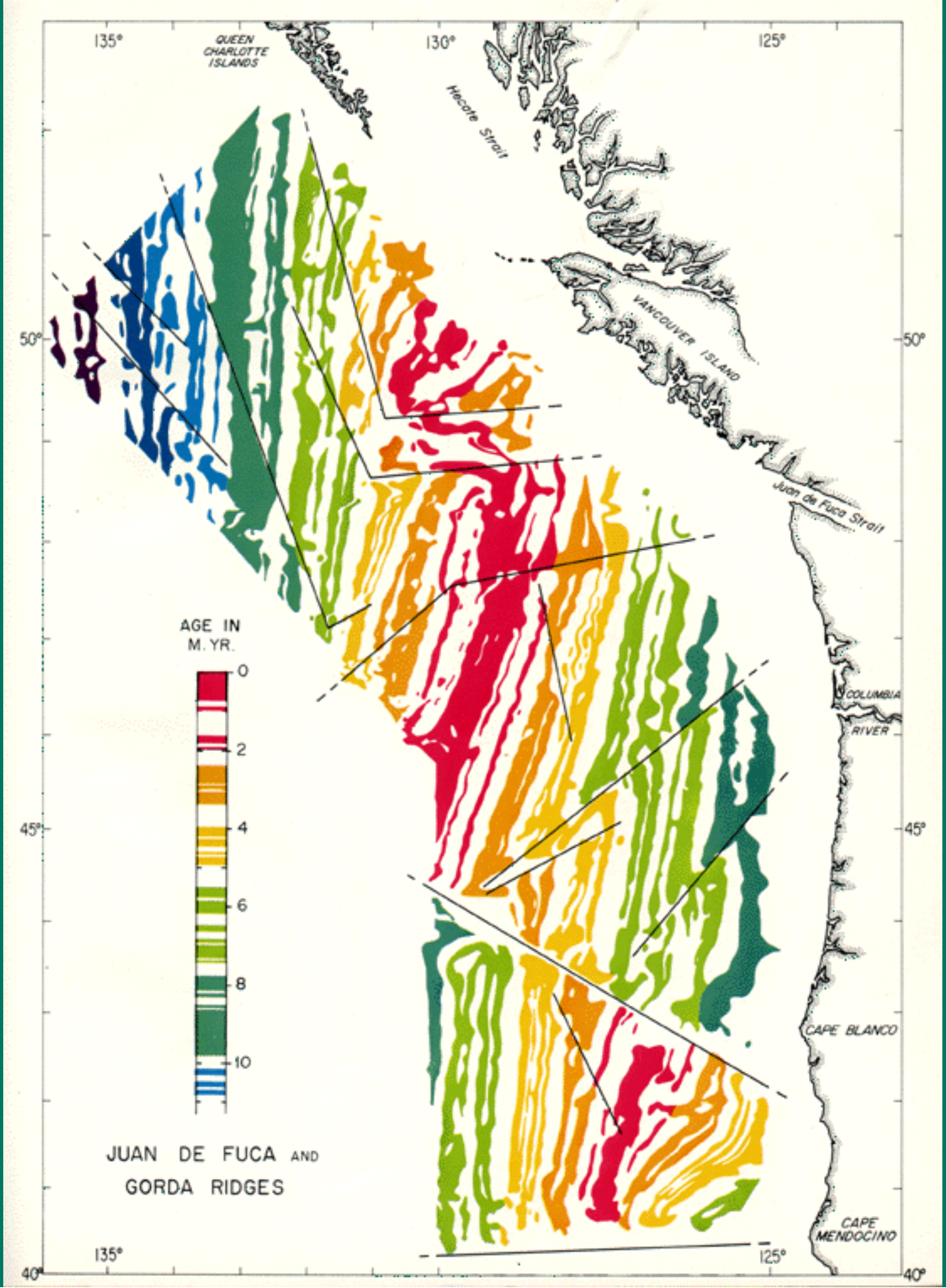



Suggested sequence of the most recent changes in polarity of the earth's magnetic field



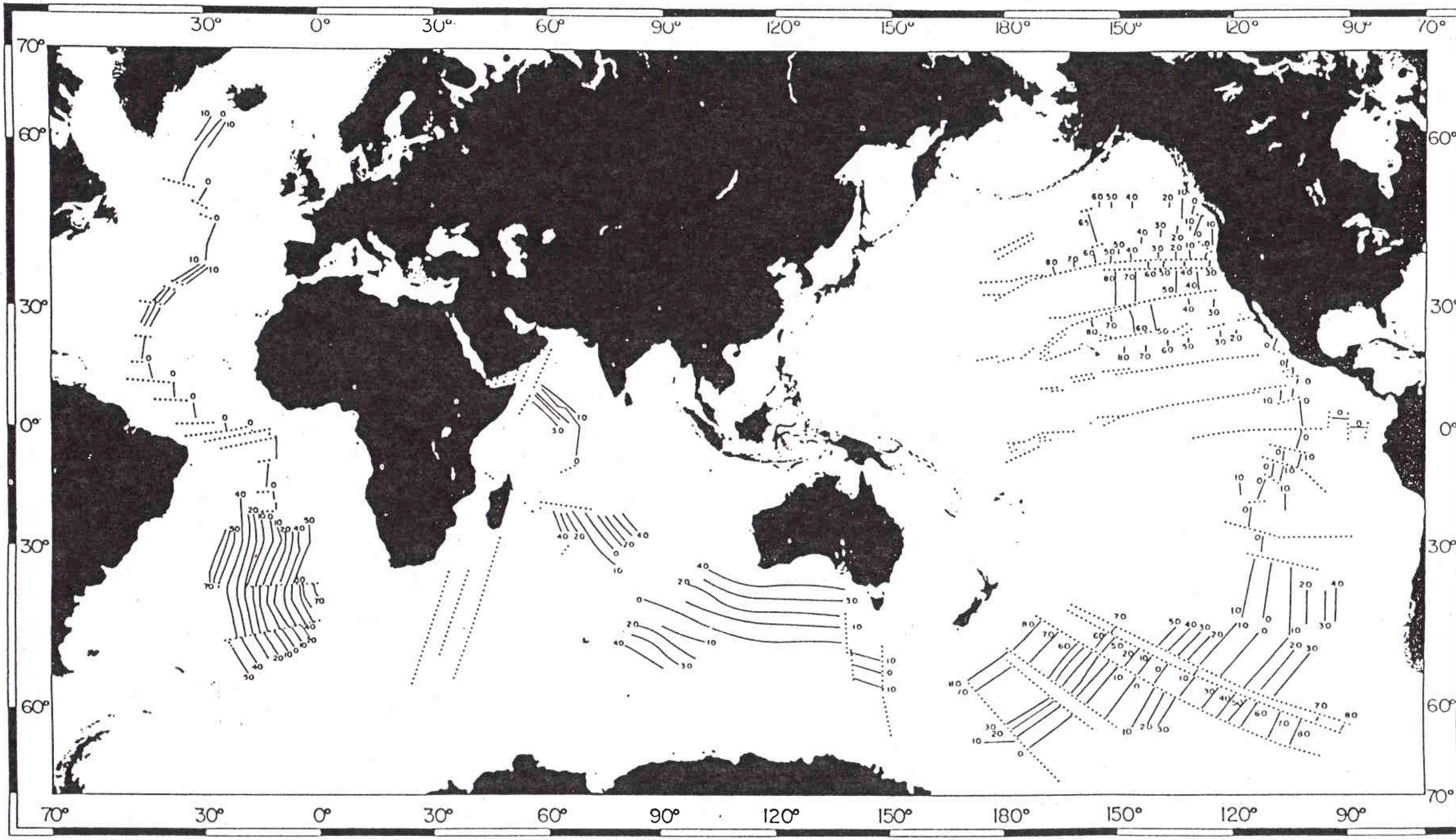

Successive versions of the radiometric time scale for reversals, showing how the discovery of polarity events changed the apparent distribution of polarity intervals (Cox et al., 1963b, 1964b; McDougall and Tarling, 1964; Doell and Dalrymple, 1966; McDougall and Chamalaun, 1966). In the corresponding histograms, $N_T$ is the total number of polarity intervals and $N$ is the number in each class interval of the histogram

Title of book about the history of plate tectonics: “The Road to Jaramillo” by W. Glen




With a magnetic polarity timescale for the last 10 Ma, you can go back to Raff and Mason's original survey of the Juan de Fuca Ridge and date the ocean floor and study the spreading history.

# Using magnetic anomalies to make a magnetic polarity reversal timescale




Isochron map of the ocean floor according to the magnetic anomaly pattern. Numbers on isochron lines represent age in millions of years. Dotted lines represent fracture zones

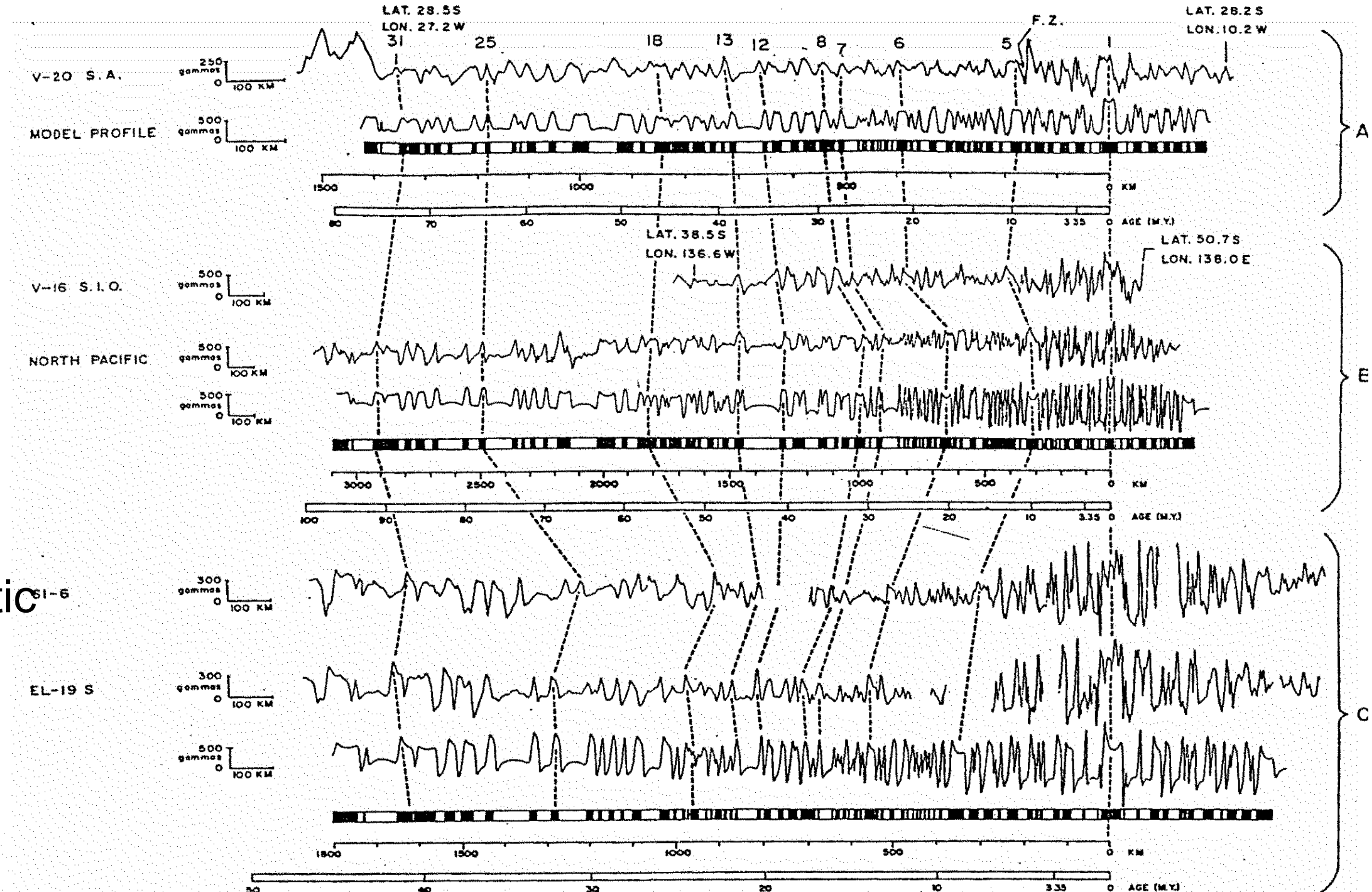
Lamont had all these great data, but needed a timescale to date the ocean floor

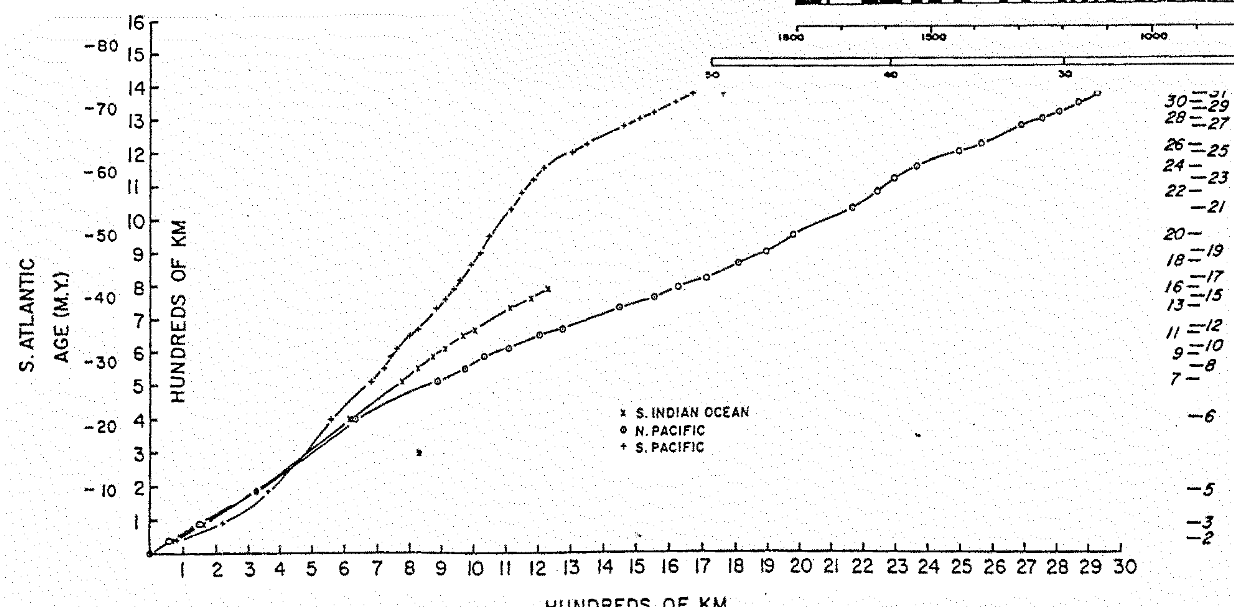
Heirtzler et al. (1968)

South Atlantic

North Pacific

Pacific-Antarctic ridge




The distance to a given anomaly in the South Atlantic (V-20 S.A.) versus distance to the same anomaly in the South Idian, North Pacific, and South Pacific oceans. Numbers on right refer to anomaly numbers.

Found that the South Atlantic had the fewest changes in spreading rate

Geomagnetic polarity timescale as of 1968

Based on a single calibration point for anomaly 2A old and extrapolating ages based on a South Atlantic profile

This timescale was extraordinary ….

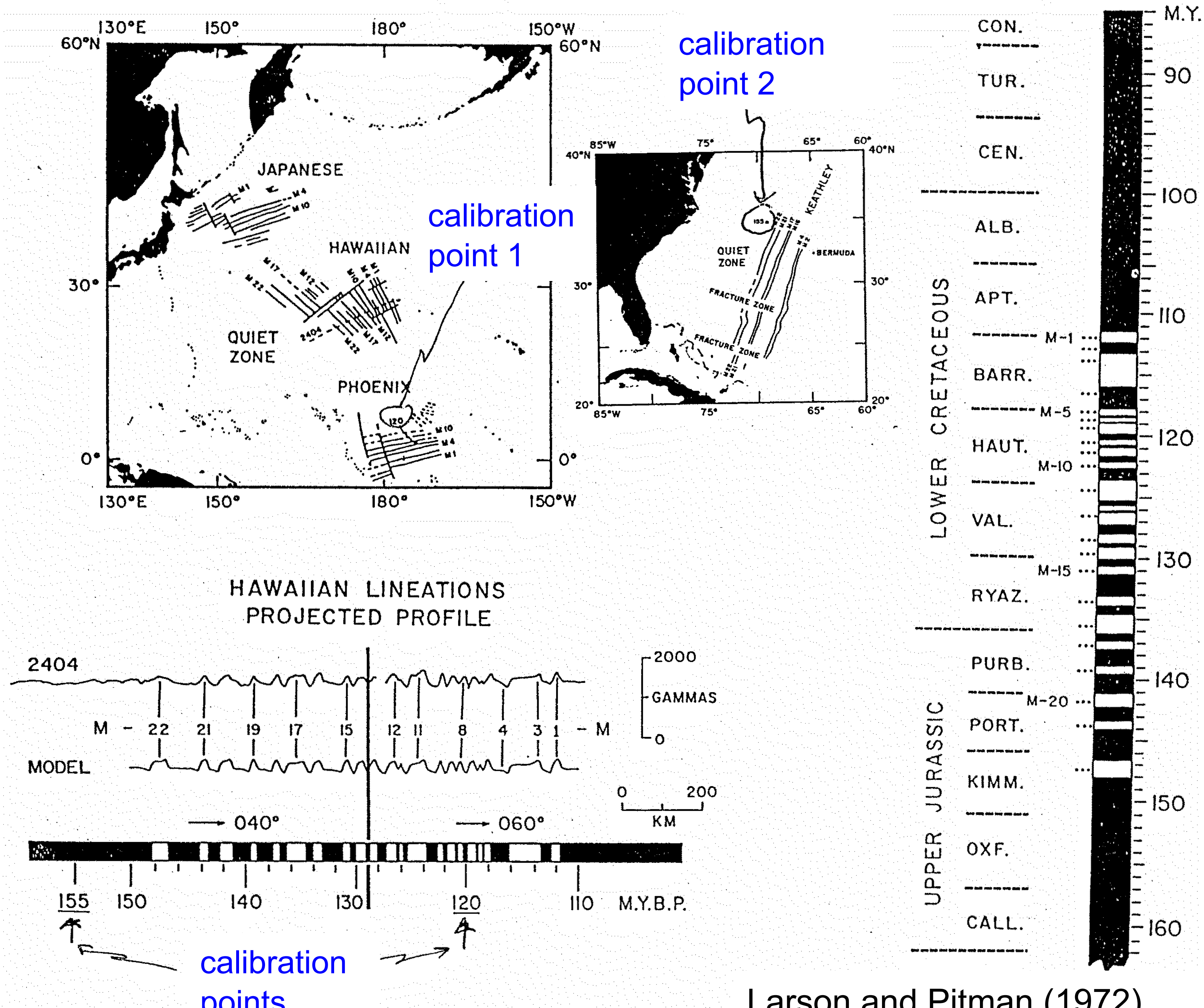
Are reversals random?


The only calibration point was a radiometric age of 3.37 Ma for the old end of anomaly 2A (the boundary between the Gilbert and Gauss epochs)

Compare the extrapolated age for anomaly 30:

Heirtzler et al. (1968) proposed ~70 Ma
The latest timescale has an age of ~65 Ma.

# 1972: Expansion of timescale to the Mesozoic – the M anomalies




Larson and Pitman (1972)

Periods of time corresponding to a magnetic anomaly are called Chrons

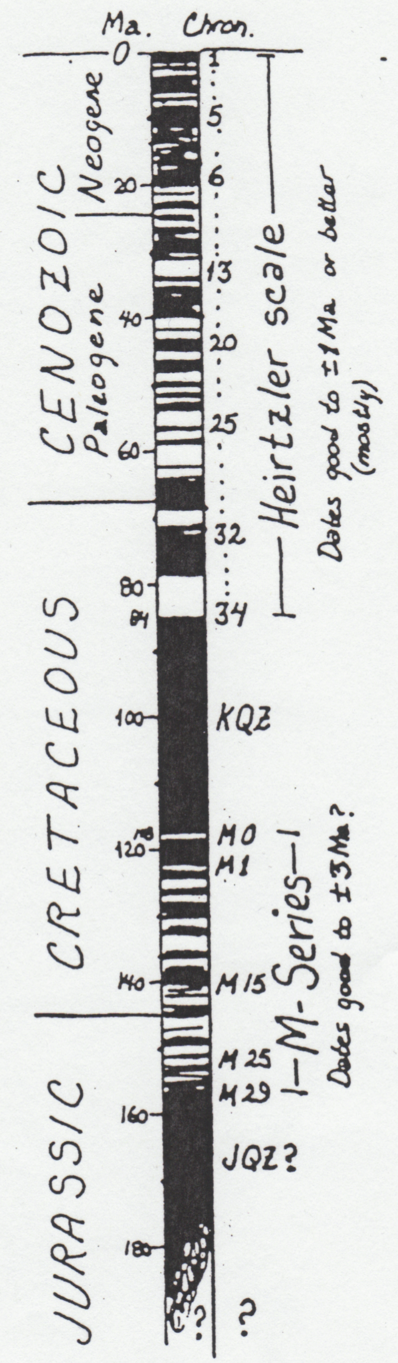
We say something happened at “Chron 5” when we mean “the time of magnetic anomaly 5”

Ages of some Chrons:

M29 = 155 Ma,
M0 = 120 Ma
34 = 84 Ma,
13 = 35 Ma,
5 = 10 Ma

Atwater

Generic Magnetic Polarity Timescale




Added two long polarity intervals (34 and 33) before 32
Added one more short reversal (M0) after M1

Put it all together: timescale for last 170 Ma

Intriguingly:

120 - 84 Ma: No linear magnetic anomalies
KQZ = Cretaceous Quiet Zones

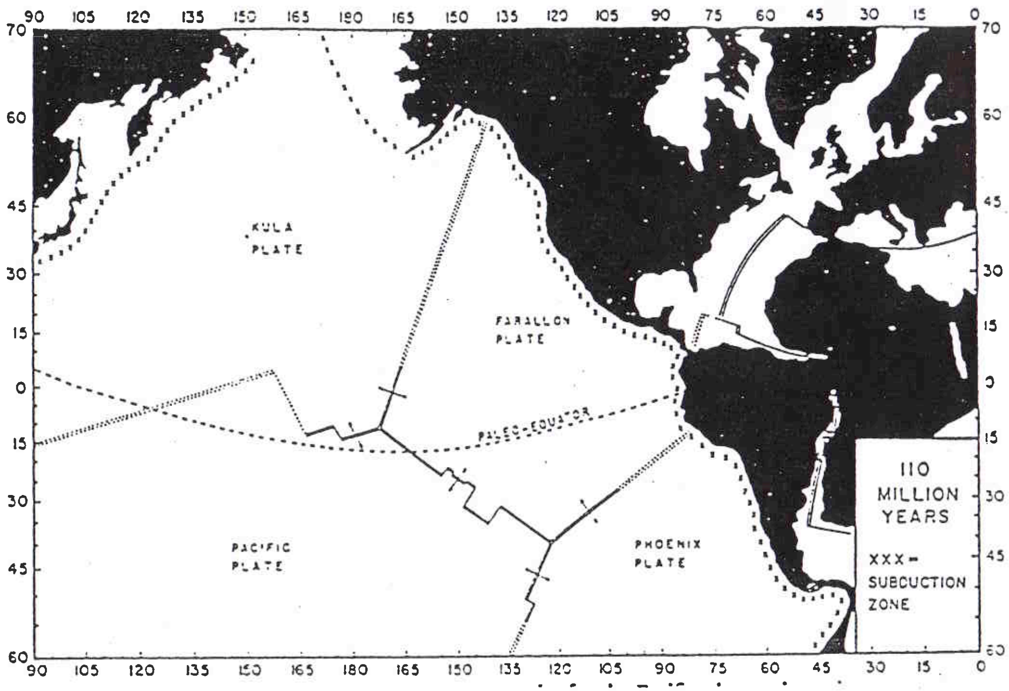
No reversals; perhaps high intensity?

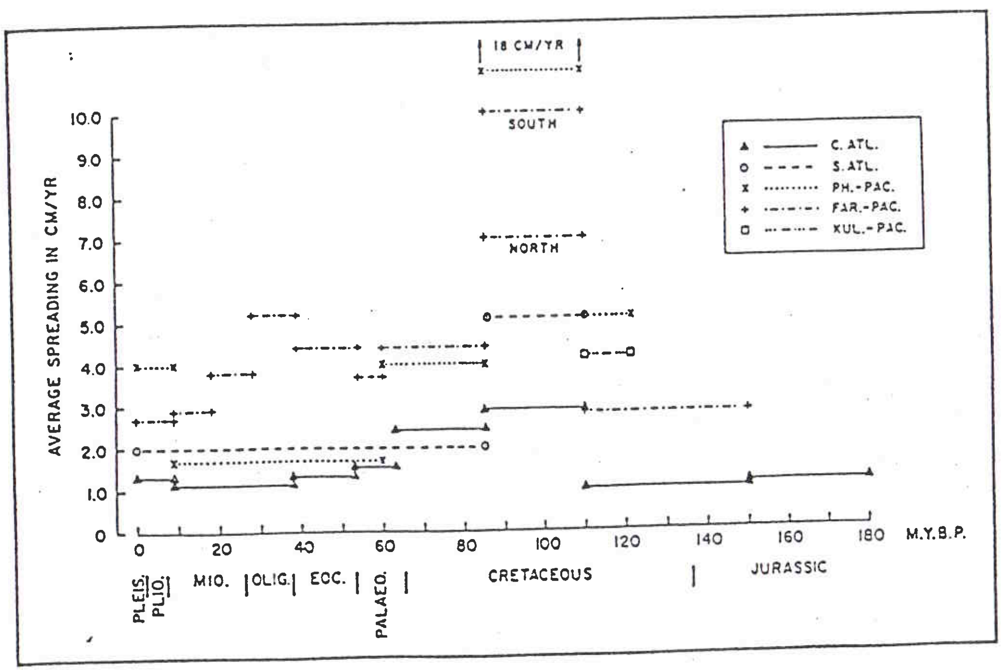
Cretaceous Long Normal Polarity Interval or the Cretaceous Superchron

Why did the field stop reversing?

Just a random, long polarity interval????

180 - 155 Ma: low amplitude magnetic anomalies
JQZ = Jurassic Quiet Zones
Rapid reversals (low field intensity ?)




Was there an episode of globally fast sea floor spreading during the Mid-Cretaceous?

Proposed in 1972 by Larson and Pitman.

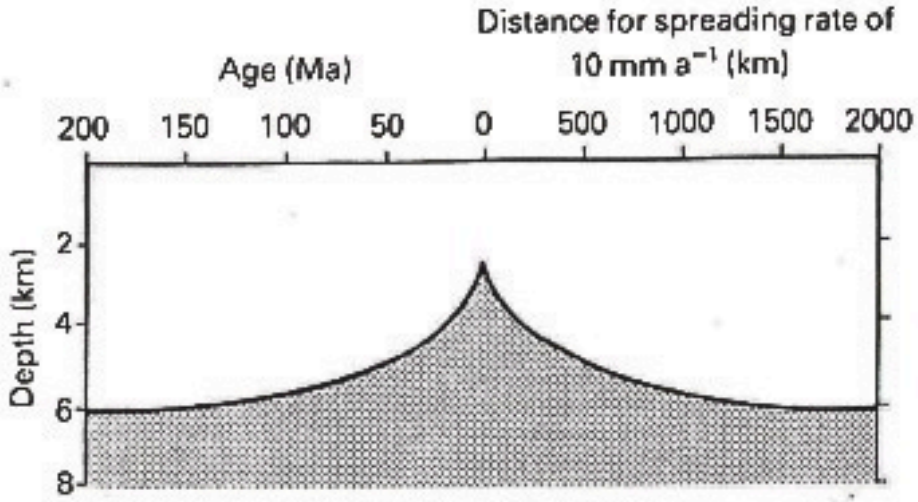
Spreading rates between anomalies M0 and 34 appeared to be unusually fast in all oceans.

Perhaps a connection with lack of polarity reversals.
Would have led to higher sea levels.

Others disputed observations; still a controversy.

Problems …
- Age of M0 slipped from 108 to 120 Ma
- Reconstructions of subducted crust
- Kula = All gone

Empirical depth/age relationship

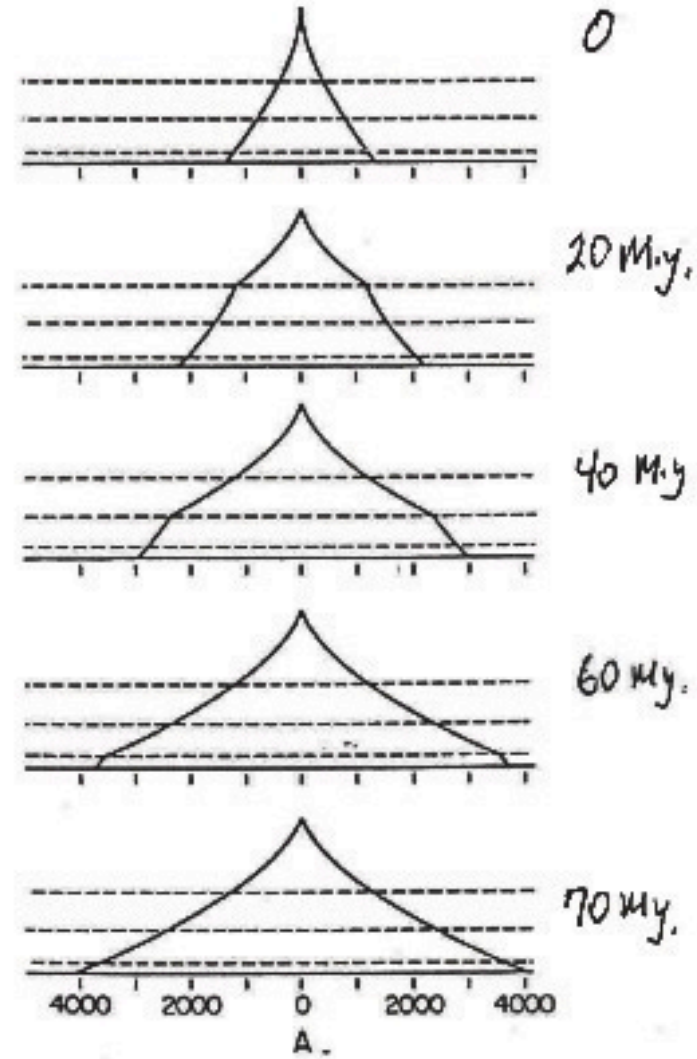



$D = 2500 + 350\sqrt{T}$ where T is age in Ma

Valid out to about 80 Ma,
then depth subsides more slowly

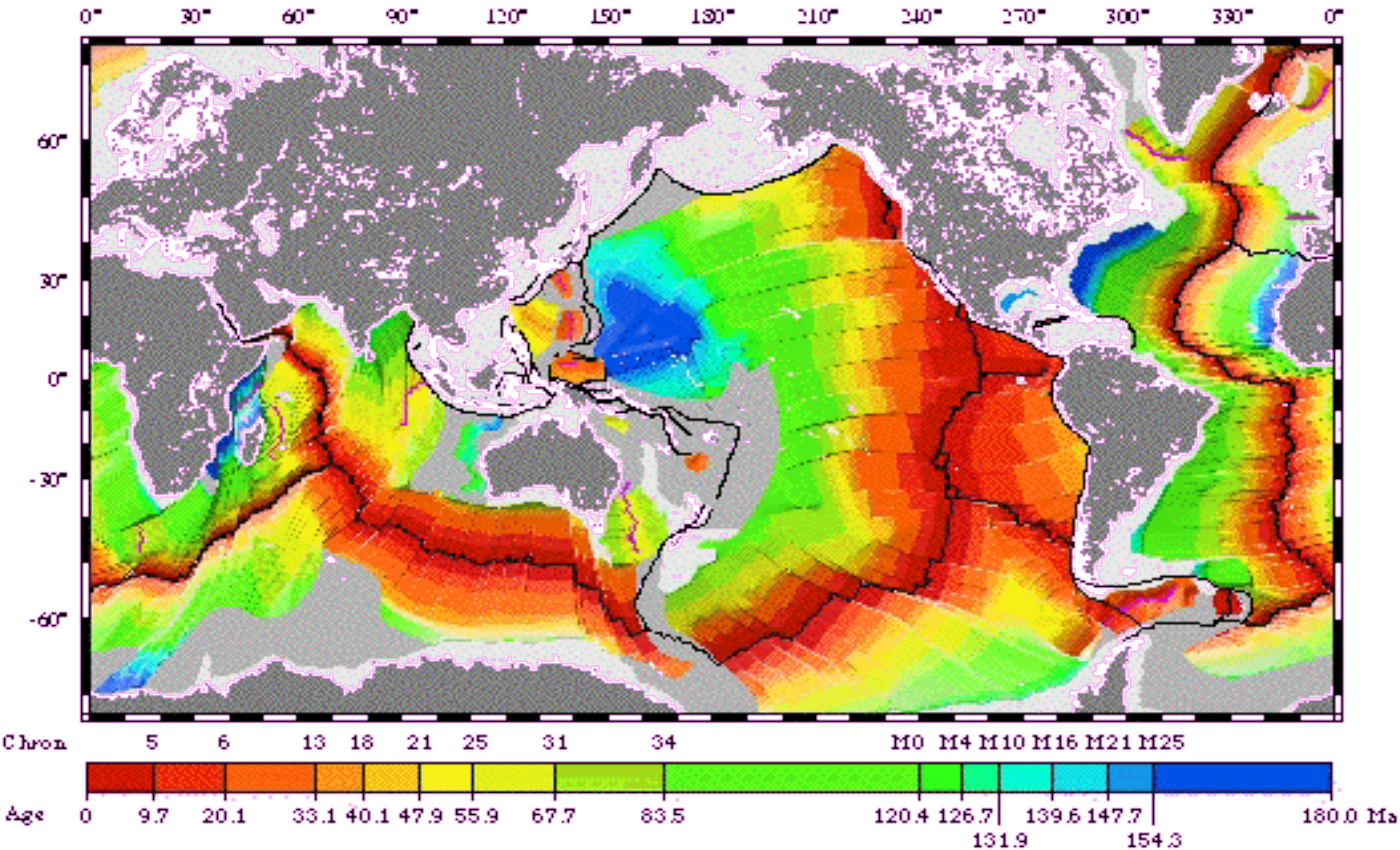
Controls long term sea level changes
Most notably - high sea levels in the late Cretaceous

effect of increasing spreading rate from 20 mm/yr to 60 mm/yr



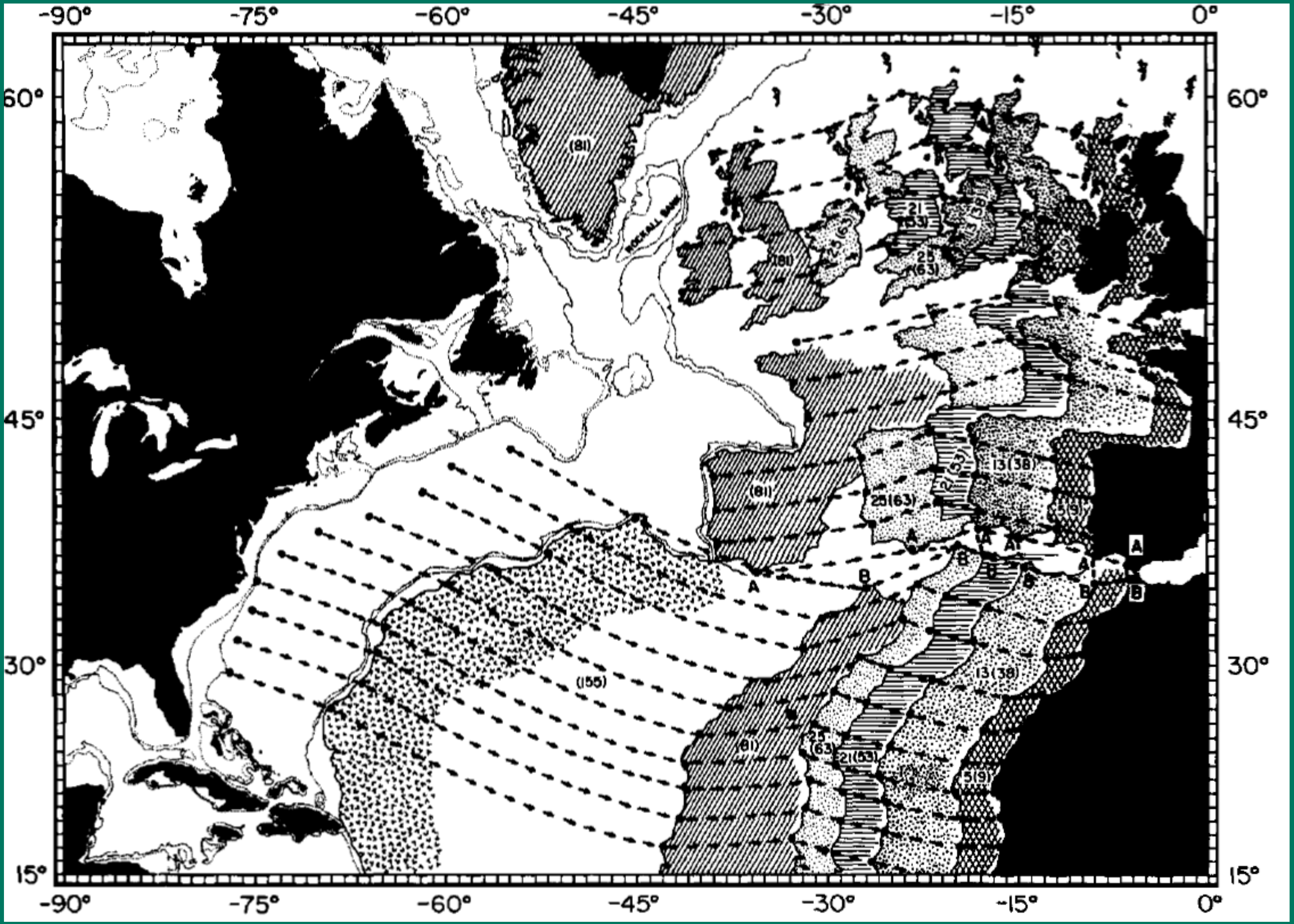
# Digital Isochrons of the Ocean Floor

R.D. Müller, W.R. Roest, J.-Y. Royer, L.M. Gahagan, J.G. Sclater



Where you have anomalies on both sides of the ridge, such as in the Atlantic, you can directly reconstruct the motions of plates.

Africa – North America + North America - Eurasia = Africa - Eurasia




Pitman and Talwani (1972)

The North Pacific is more difficult because half the anomaly record ( the Farallon and Kula plates) has been subducted. But if you assume spreading was symmetrical you can deduce a lot.

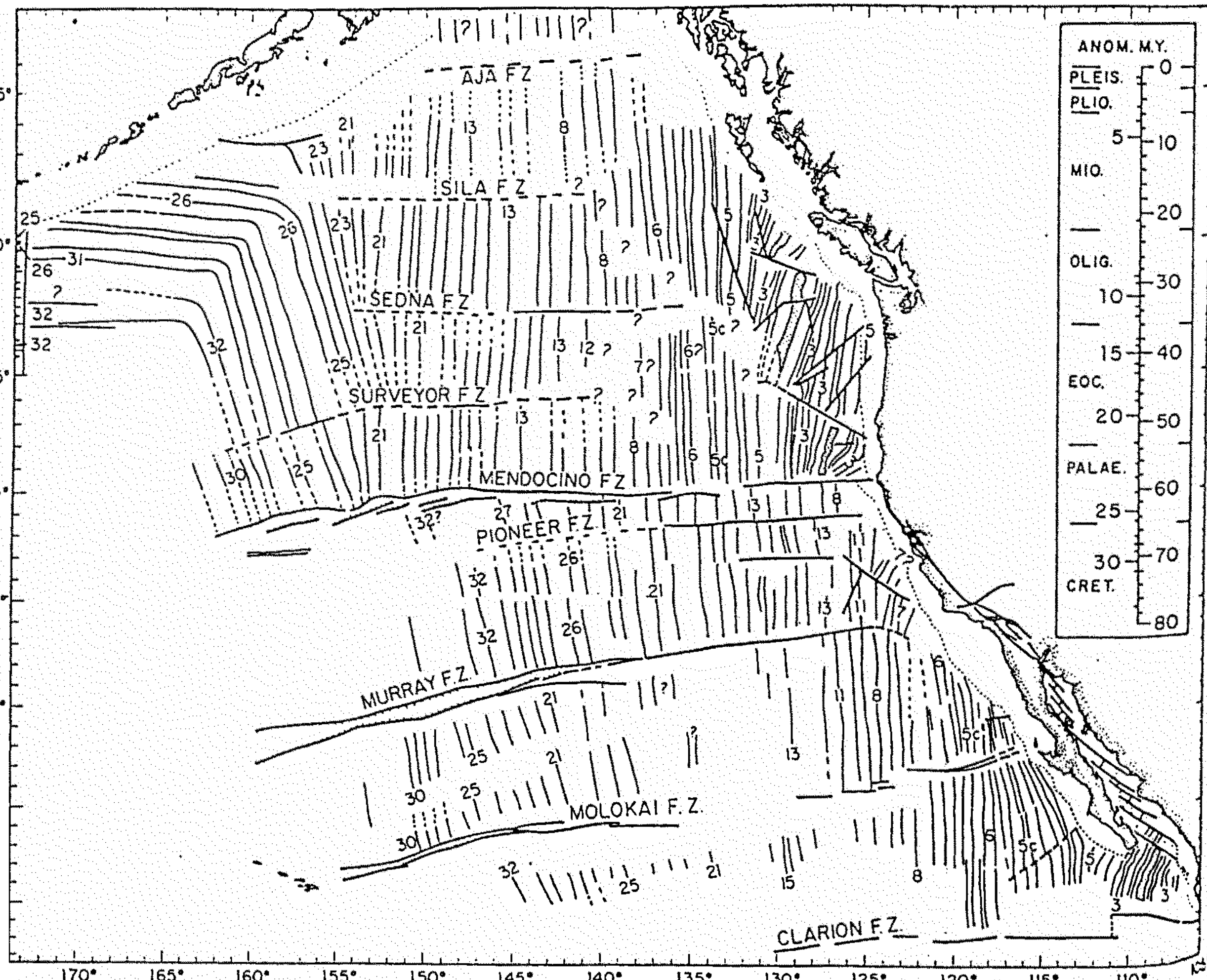
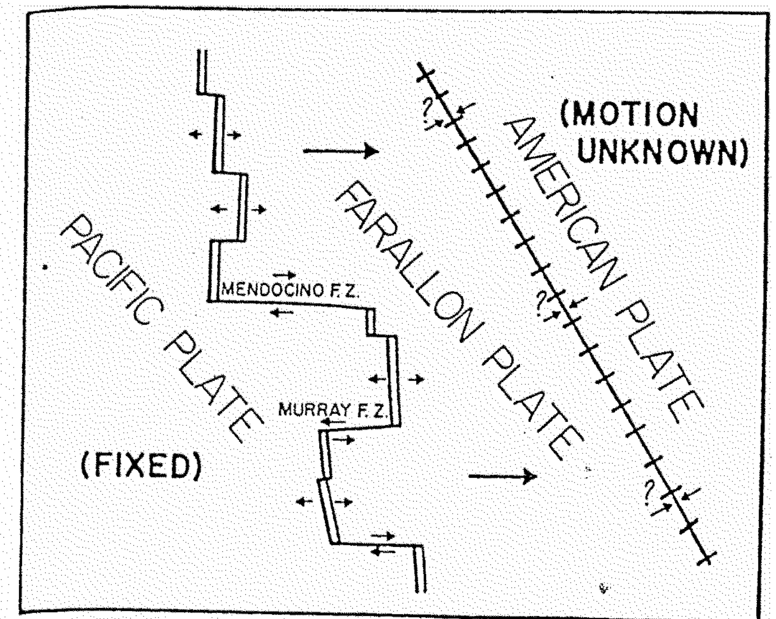


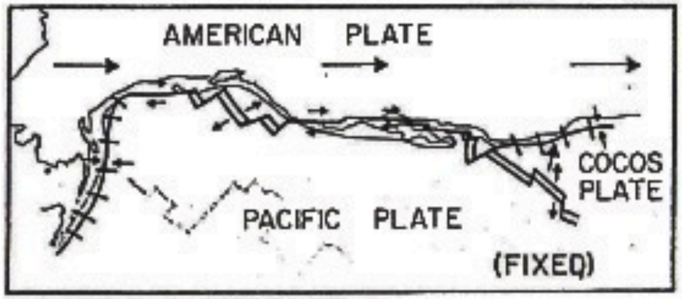

Figure 1. Magnetic anomalies in the northeast Pacific from Atwater and Menard (1970).

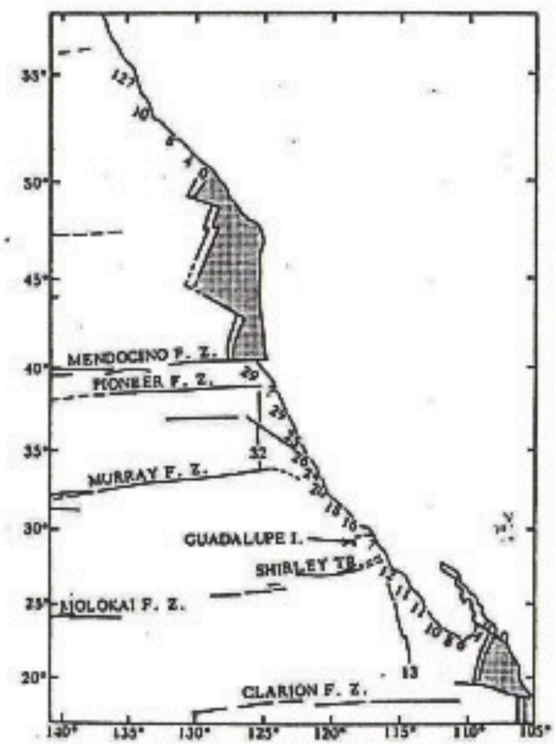


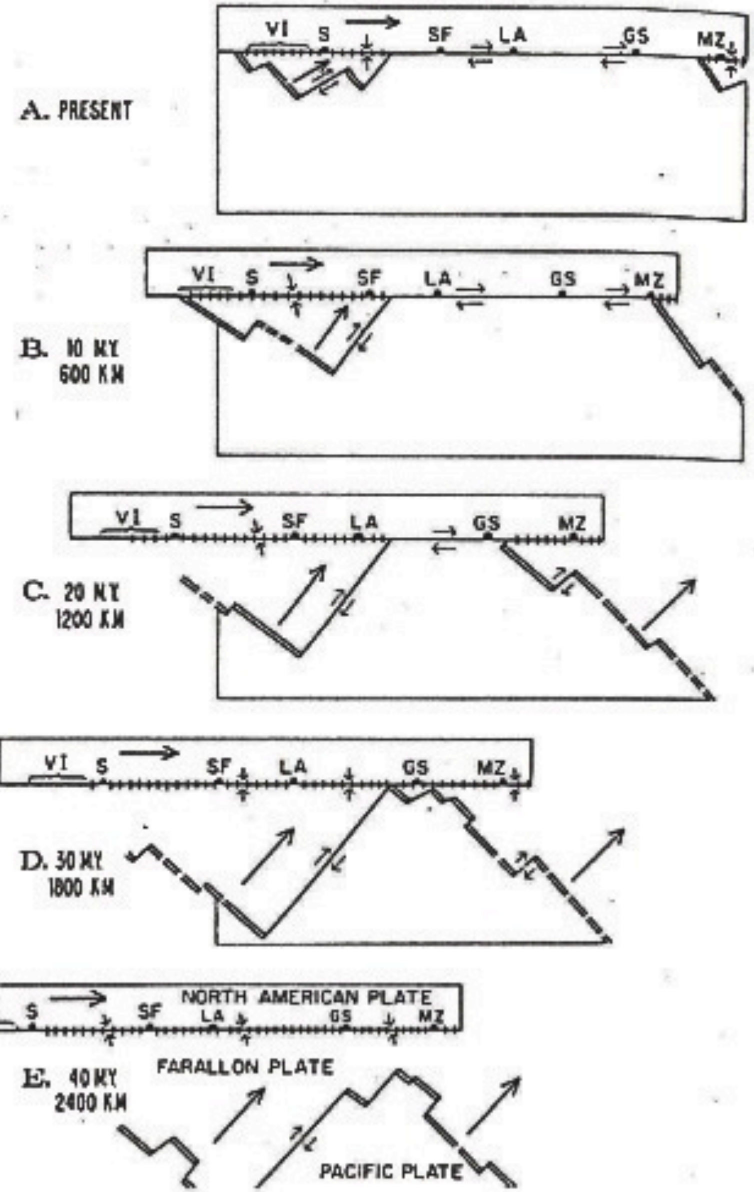

Magnetic anomalies record the configuration of the Pacific-Farallon ridge as it approached the trench along the western edge of North America.

Atwater (1970)

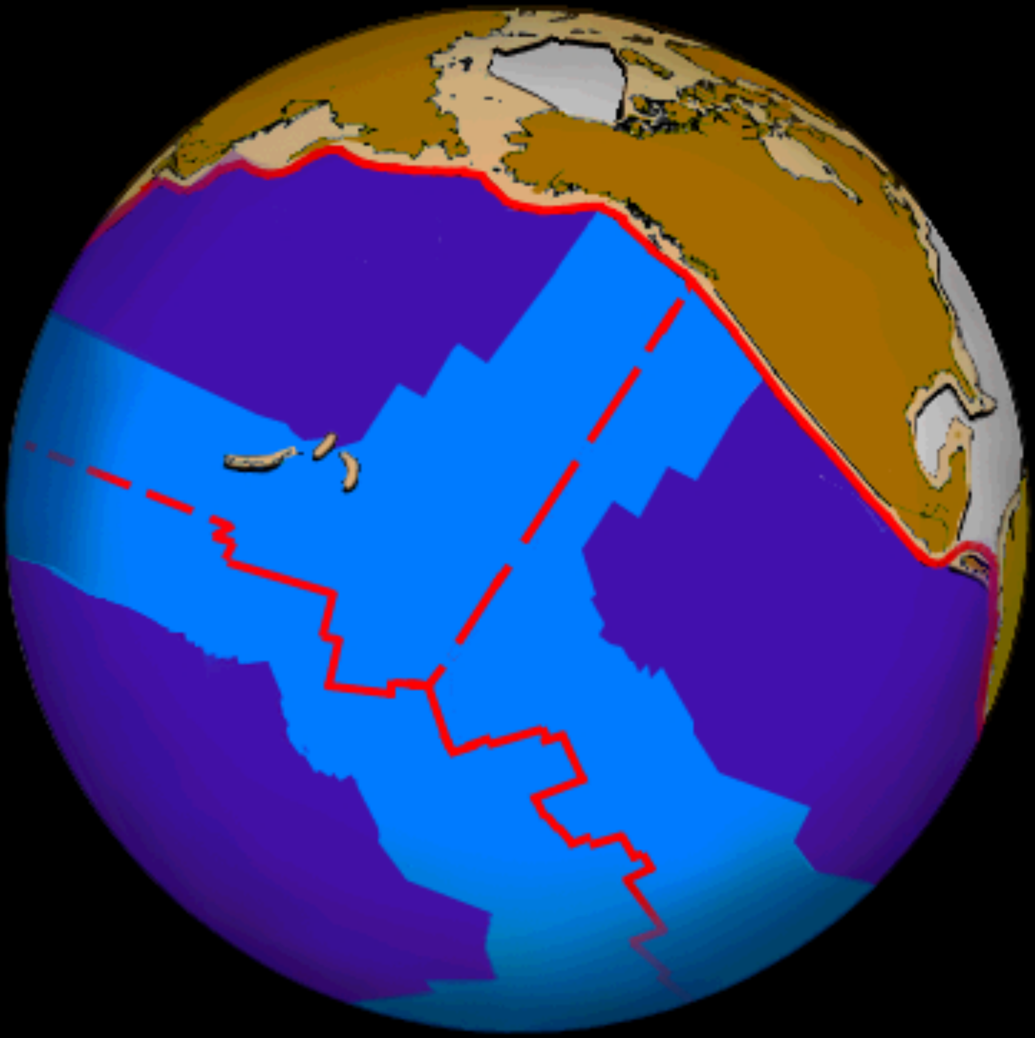
Interaction of Pacific and Farallon plates with North America based on Magnetic Anomalies



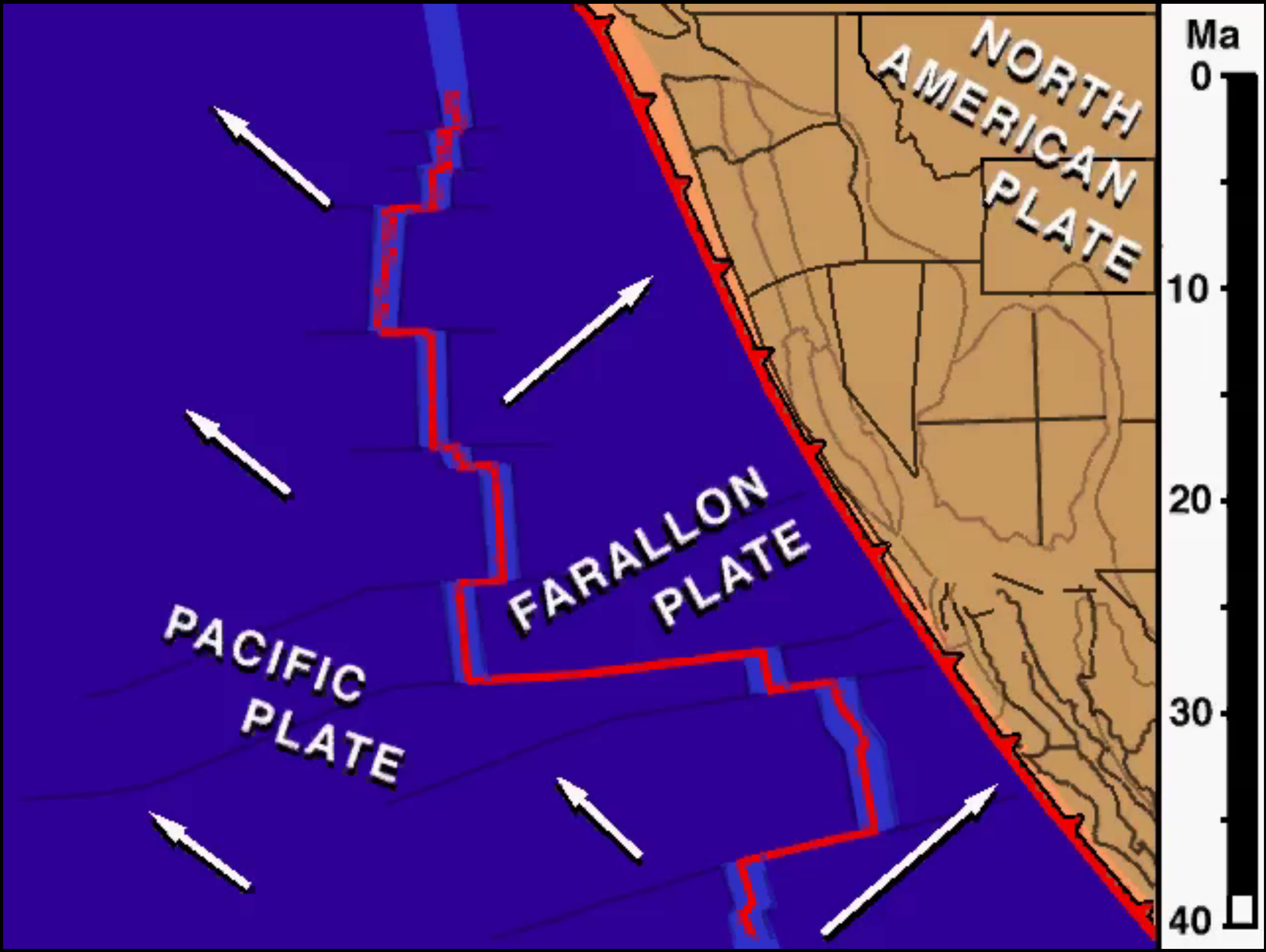



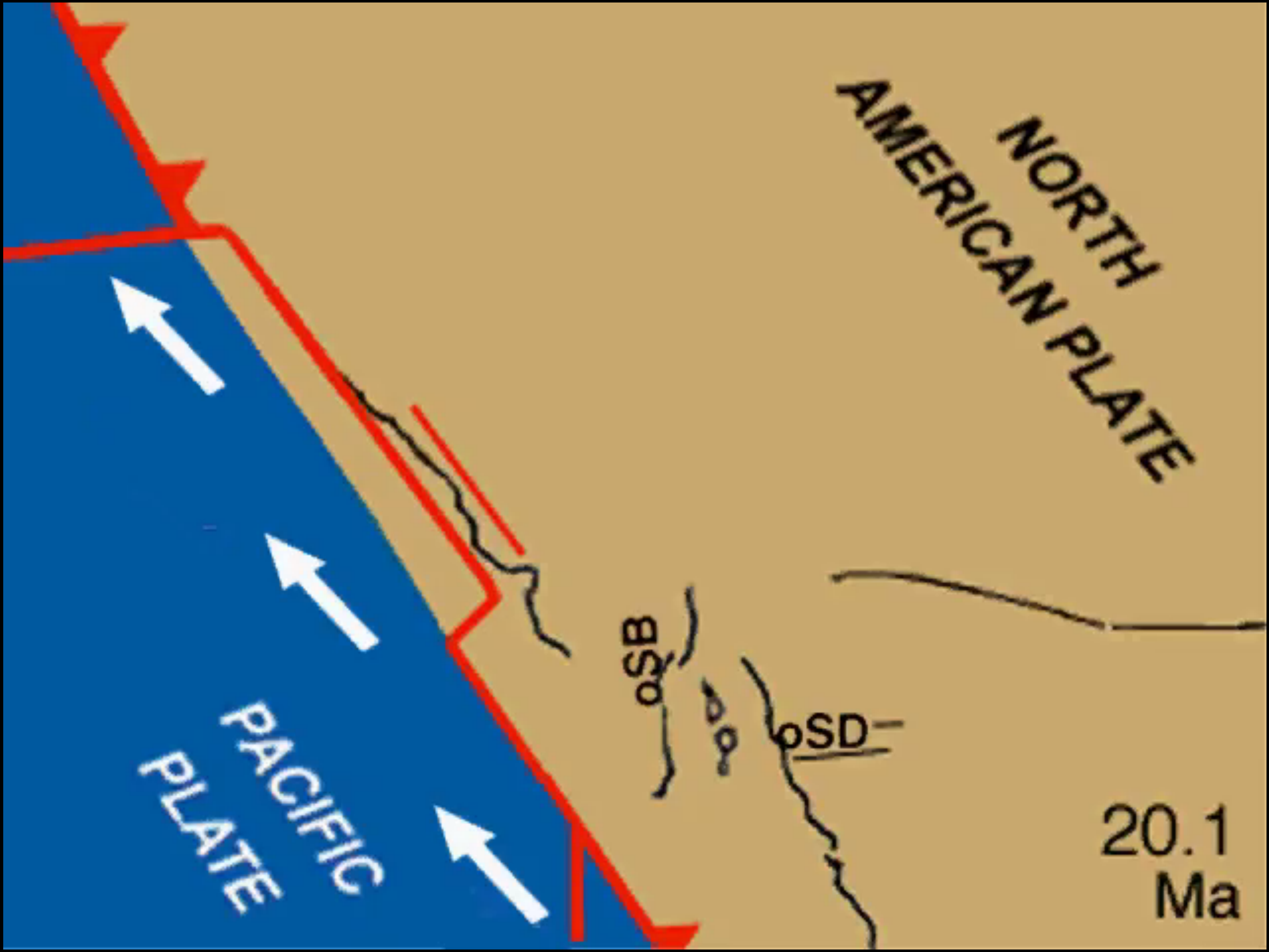

Atwater (1970)



80 Ma



NORTH AMERICAN PLATE
FARALLON PLATE
PACIFIC PLATE
Ma
0
10
20
30
40

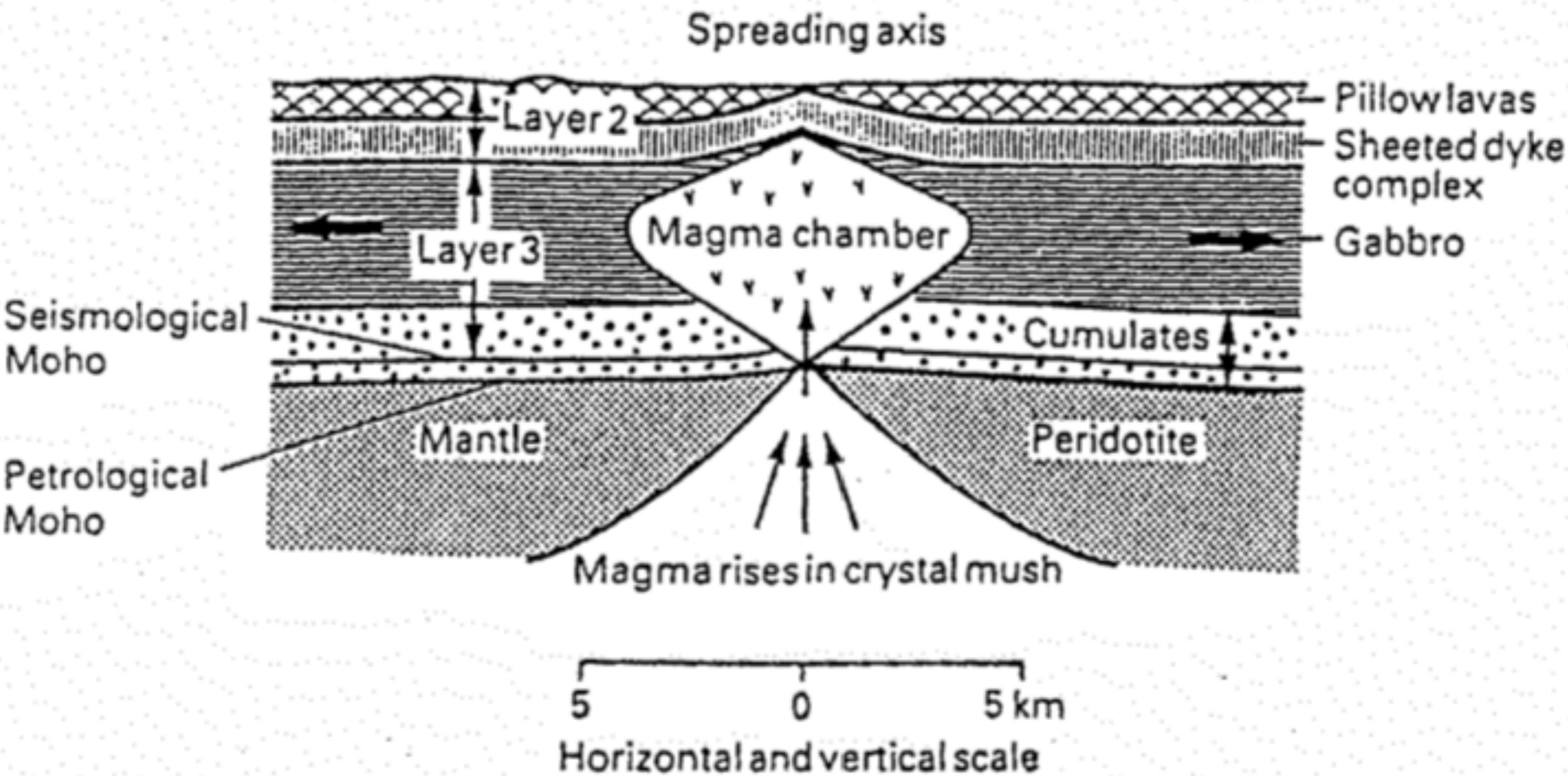


NORTH AMERICAN PLATE
PACIFIC PLATE
SB
SD
20.1 Ma

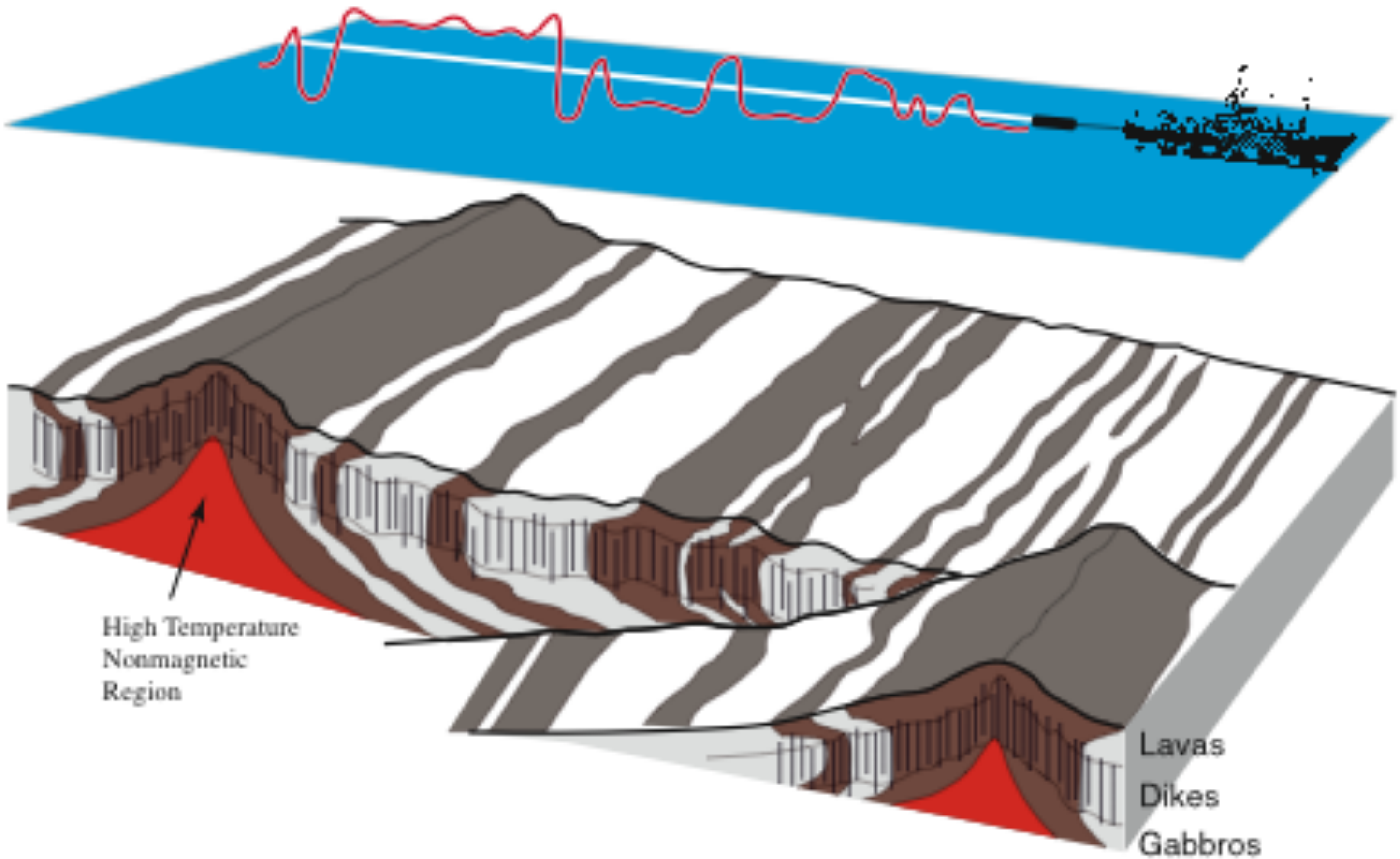
# Composition and structure of the oceanic crust

Magnetic anomalies are generated from three layers in the oceanic crust:
:

Rapidly quenched pillow basalts (extrusives) in layer 2A
Sheeted dykes (intrusives) in layer 2B
Slowly cooled gabbros in Layer 3



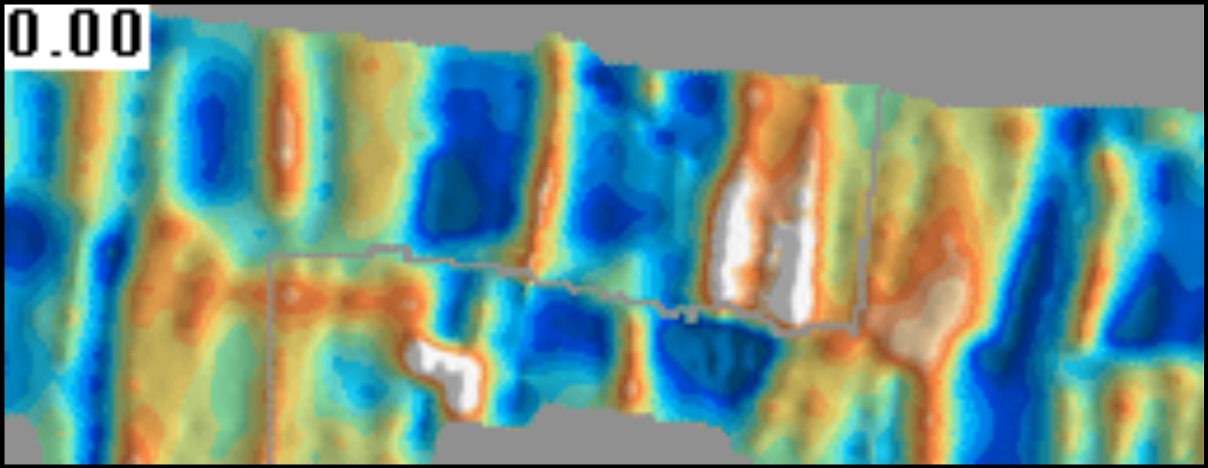
Gee and Kent (2007)

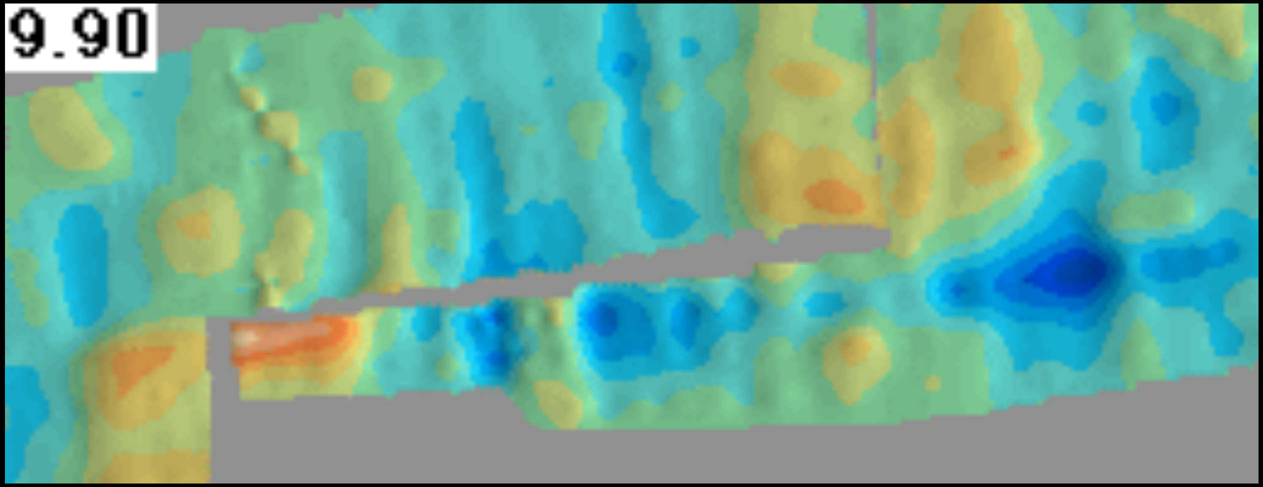



The shape of the polarity boundary varies from layer to layer and reflects how it is formed:

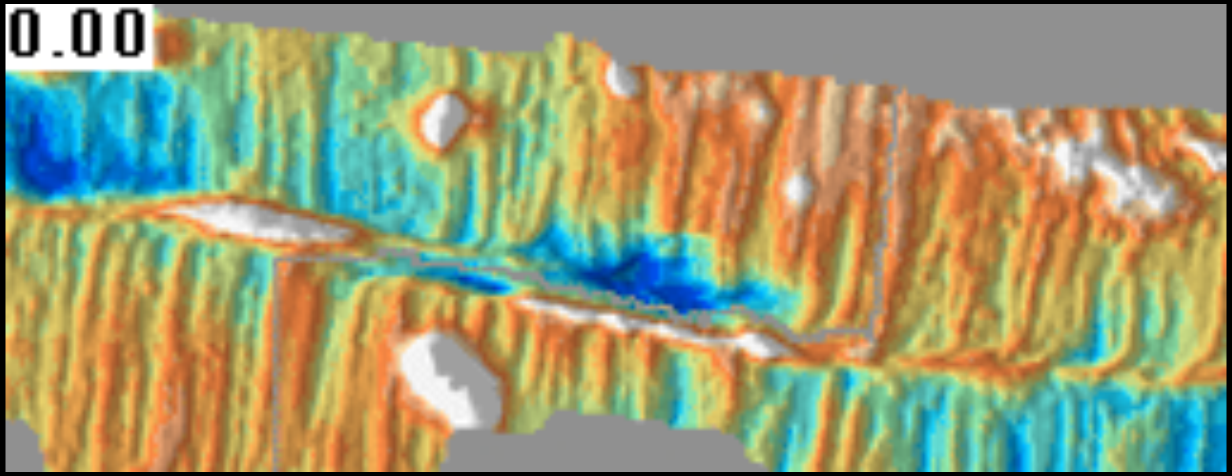
In the Pillow basalts it is about 2 km wide and slopes inward
In the dikes it may be only a few 100 m's wide and is vertical
In the gabbros it is broad (10-15 km) and slopes gently outwards following the cooling isotherms

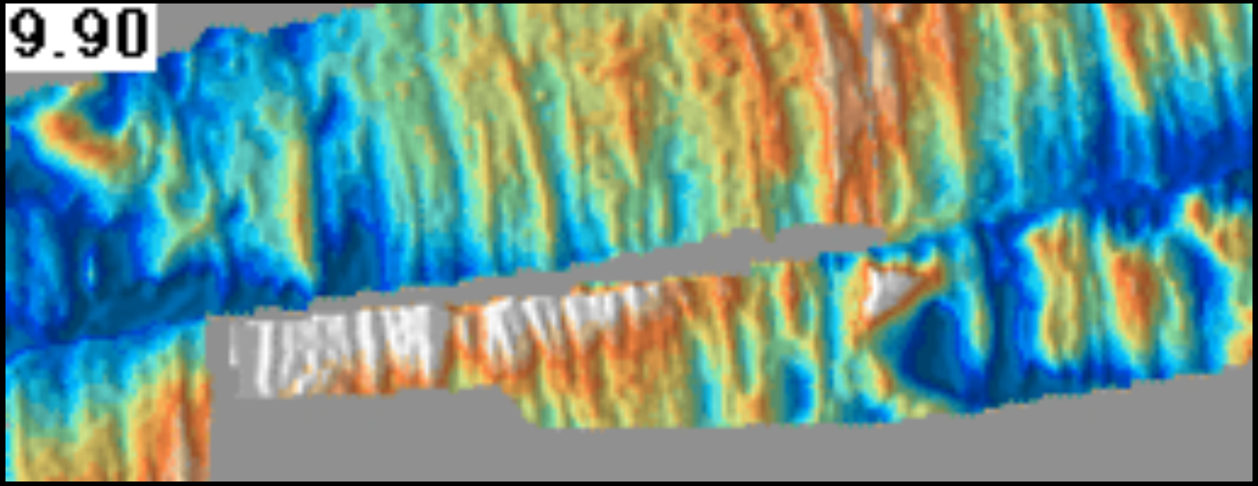
## Reconstruction: magnetic anomalies

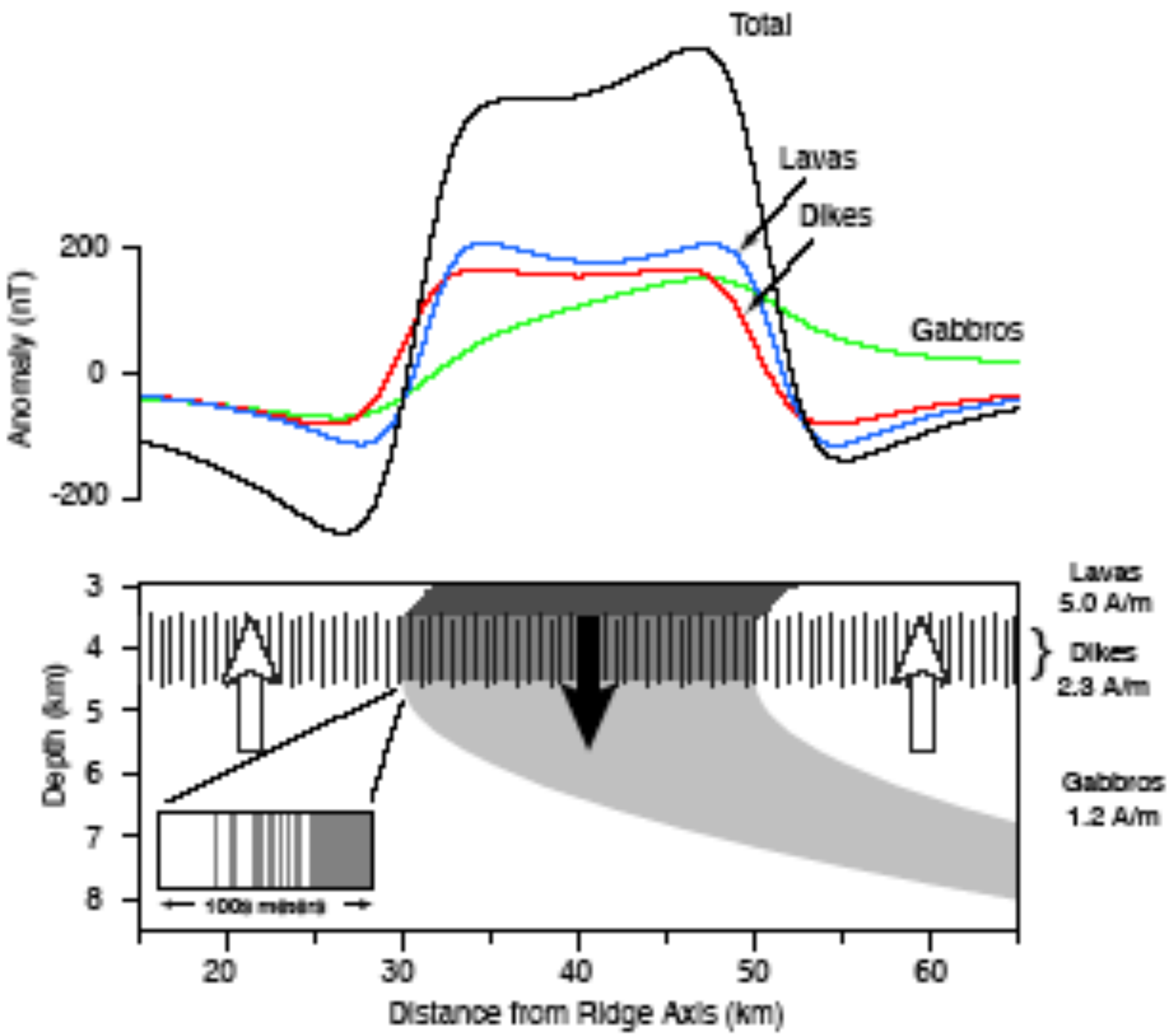


# Reconstruction: bathymetry






Gee and Kent (2007)

magnetization units:
A/m= amps/meter

Observed anomalies are a composite of three layers

The pillow basalts of layer 2A, the extrusives, are the most strongly magnetized. Although this layer is only 500 m thick, it is the most important contributor to anomalies

The intrusive dikes, layer 2B, are about half the strength of the extrusives. This layer is about 1 km thick.

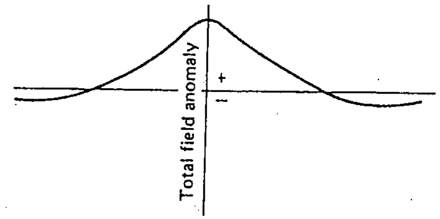
The gabbros, Layer 3, are the weakest, but since this layer is about 4 km thick it is also important

So, the ratio of magnetization in the three layers is closer to
5.0 to 2.3 to 1.2

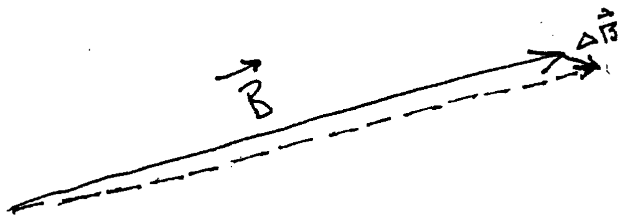
# Basic Theory of Magnetic Anomalies

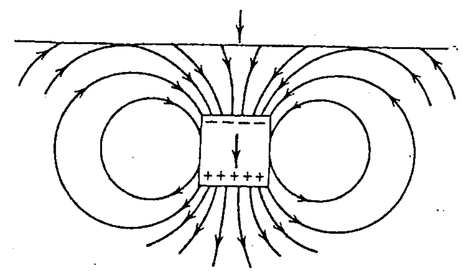
Consider the magnetic anomaly over a 2-D body on the sea floor "at the pole" – i.e. where the Inclination of the ambient field is 90°

Total field magnetometers (e.g. proton precession) measure the component of the anomalous (crustal) field in the direction of the ambient (main) field. That is, since the ambient field is >> than the anomalous field, the component of the anomalous field ⊥ to the ambient field has no effect on the total field value.




Ambient Field



observation level

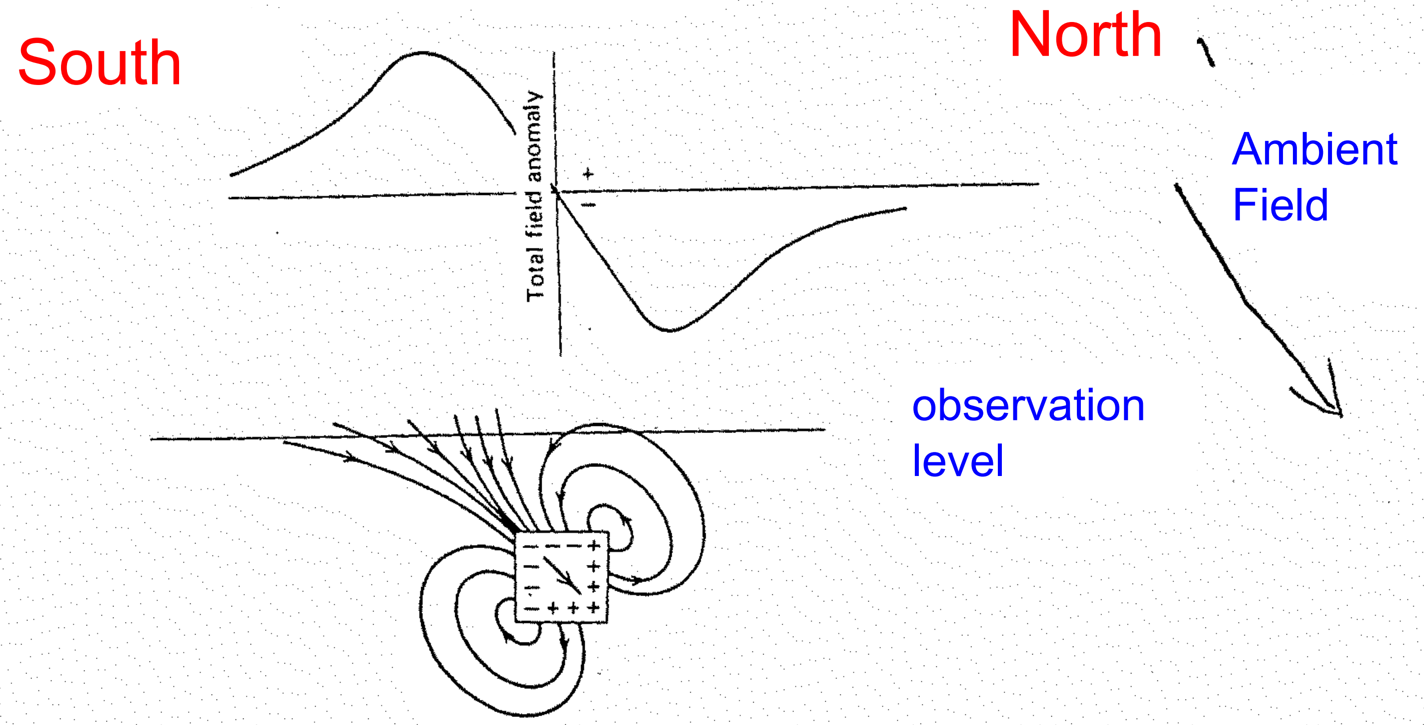
Dobrin (1976)

Consequently, it is relatively easy to visualize the shape of the anomaly over simple magnetic bodies.

Note that the anomaly is positive over the center of the body and slightly negative beyond the edge of the body.

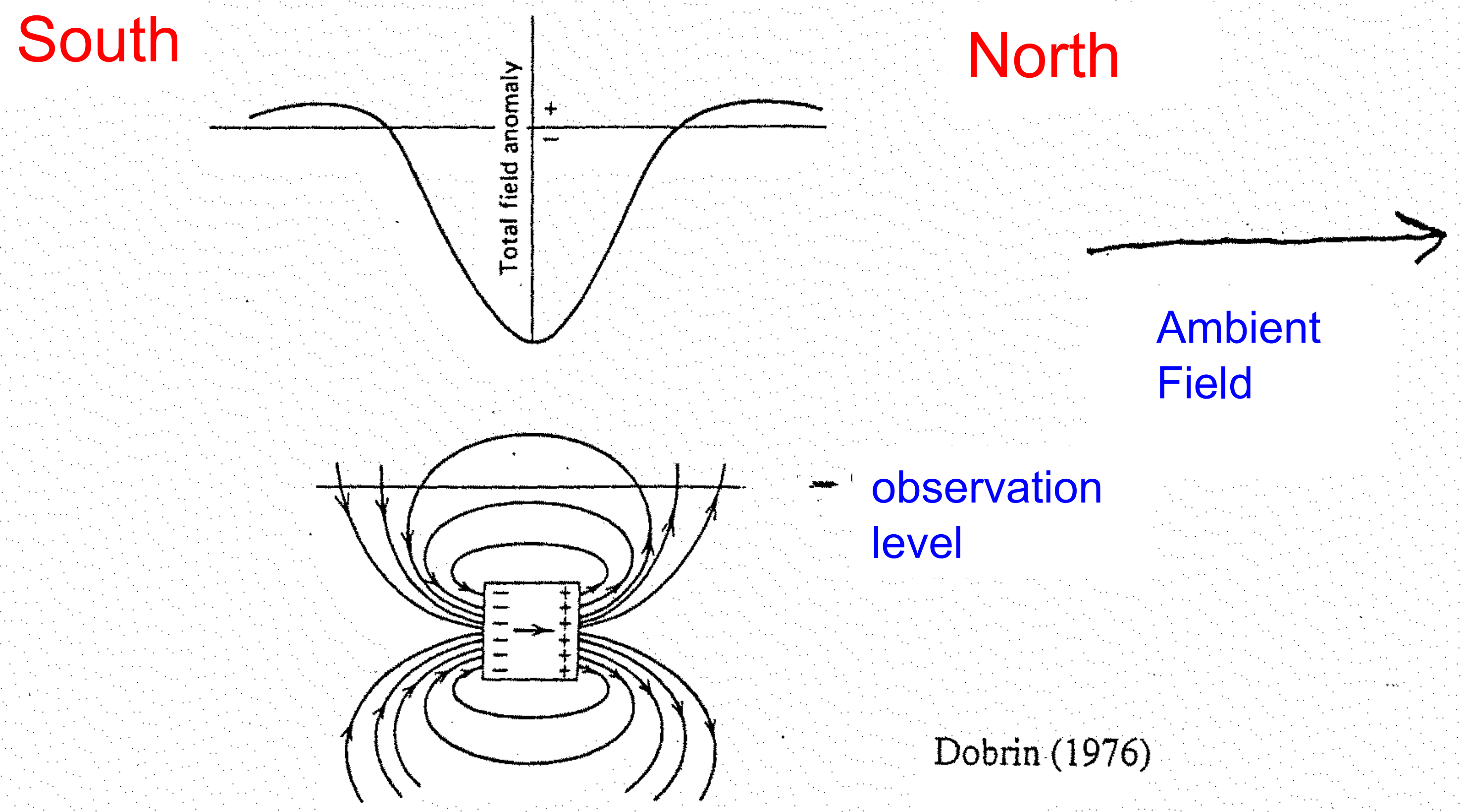
Other Simple Examples:

Consider the magnetic anomaly over a 2-D body striking east-west at a middle latitude - where the Inclination is ~ 45°




Note that the positive peak is offset towards the south side of the body. We say the anomaly is "skewed."

Finally, consider the anomaly over a 2-D body striking east-west at the equator - where the Inclination is 0°.

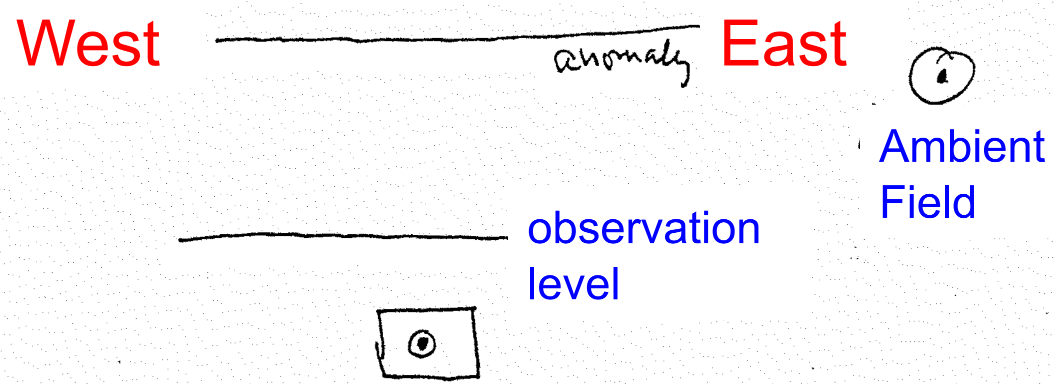



Dobrin (1976)

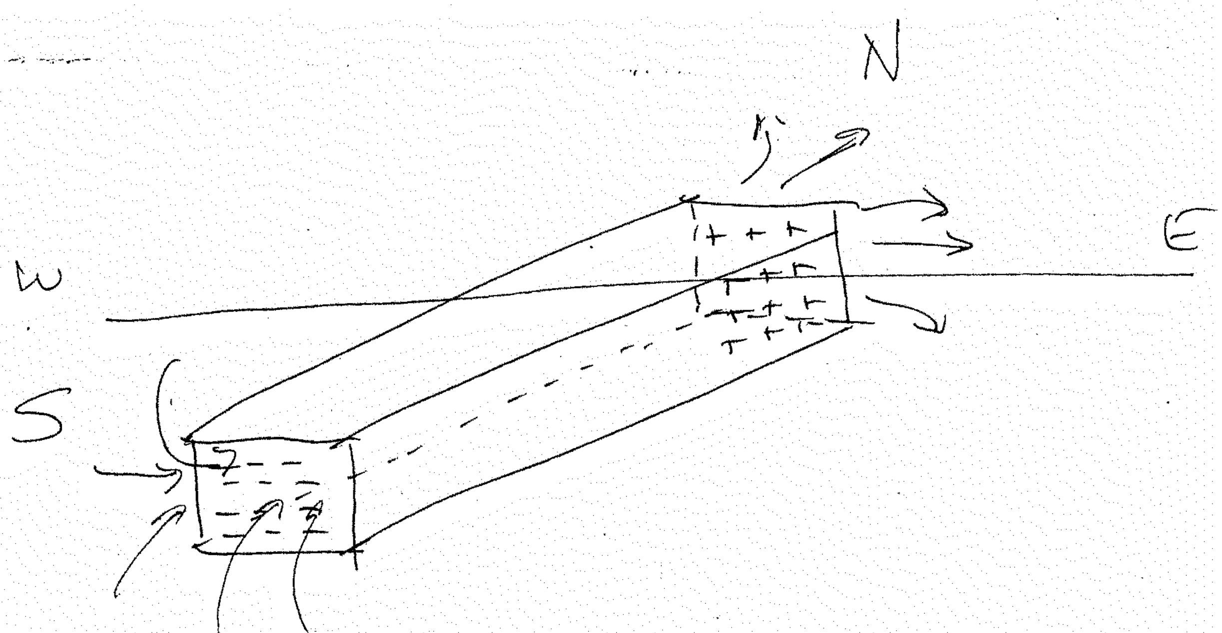
Note that the anomaly over the center of the body is negative or "upside-down". Example – anomalies over the Galapagos Spreading Center

One final example:

Consider the magnetic anomaly over a 2-D body striking North-South at the equator – where the Inclination is zero and "into the board."

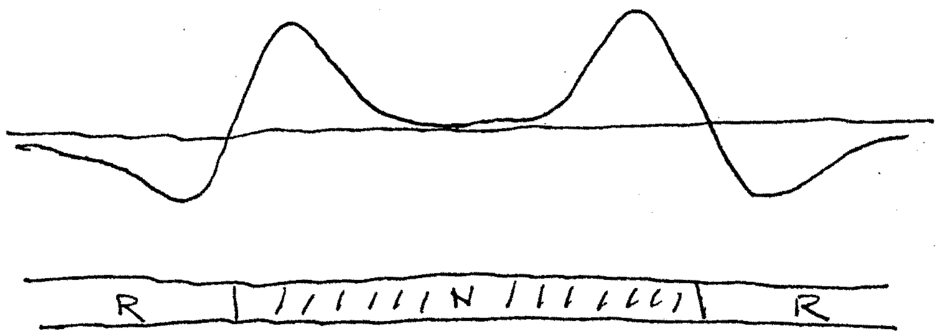



In this case there are no field lines outside of the body – and no anomaly! Example: Equatorial Atlantic, East Pacific Rise near equator.

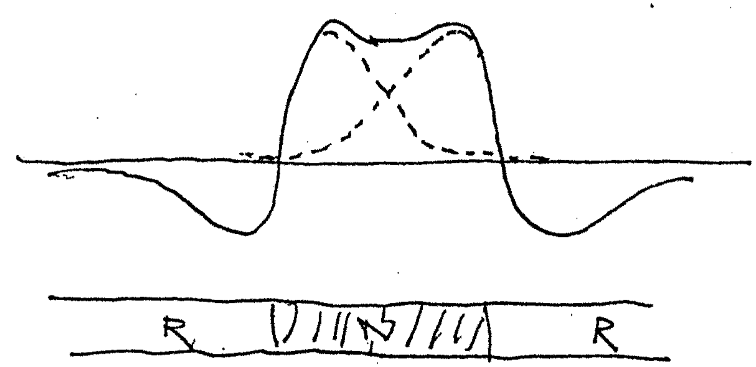


You can think of magnetic anomalies as "composites" of edge effects:

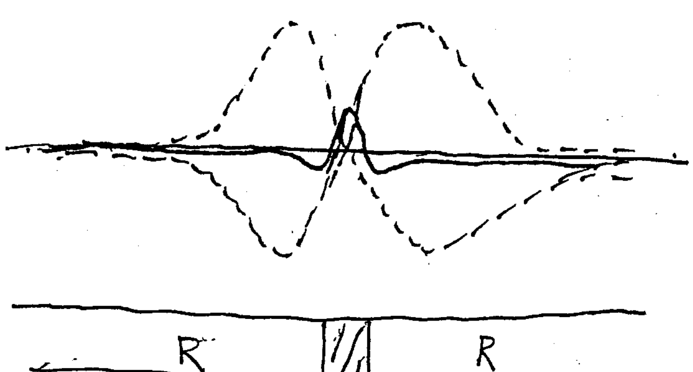
If the reversal boundaries are far apart, the edge effects are distinct and the anomaly goes to zero in the center.




The anomalies we "normally" see at intermediate spreading centers is a composite of two edge effects.




At slow spreading rates, the same two edge effects nearly cancel:



RESULTS

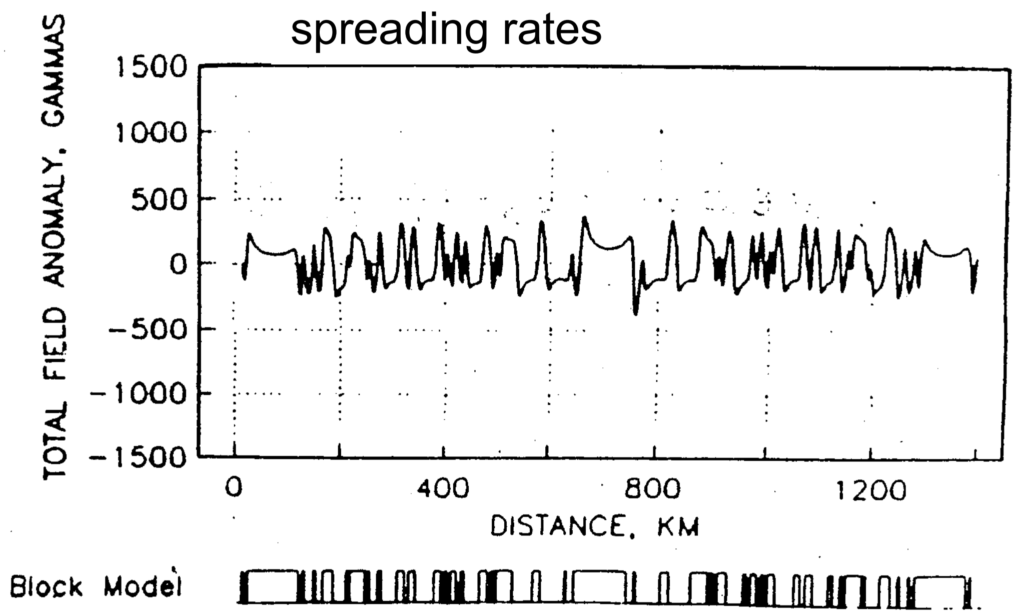
SPREADING RATES

<u>slow</u>: lose all short wavelength events + geologic noise
(Atlantic, W. Indian, Arctic)
so poor identification, poor histories

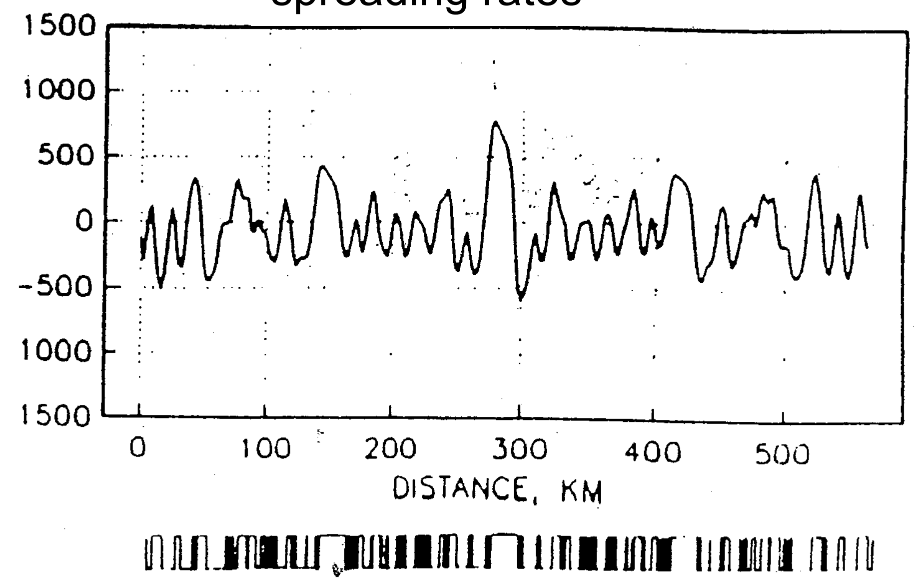
<u>med</u> good resolution, good ident
(Pacific, E. Indian)

<u>fast</u> —"— + can study short events
(south-central Pacific)

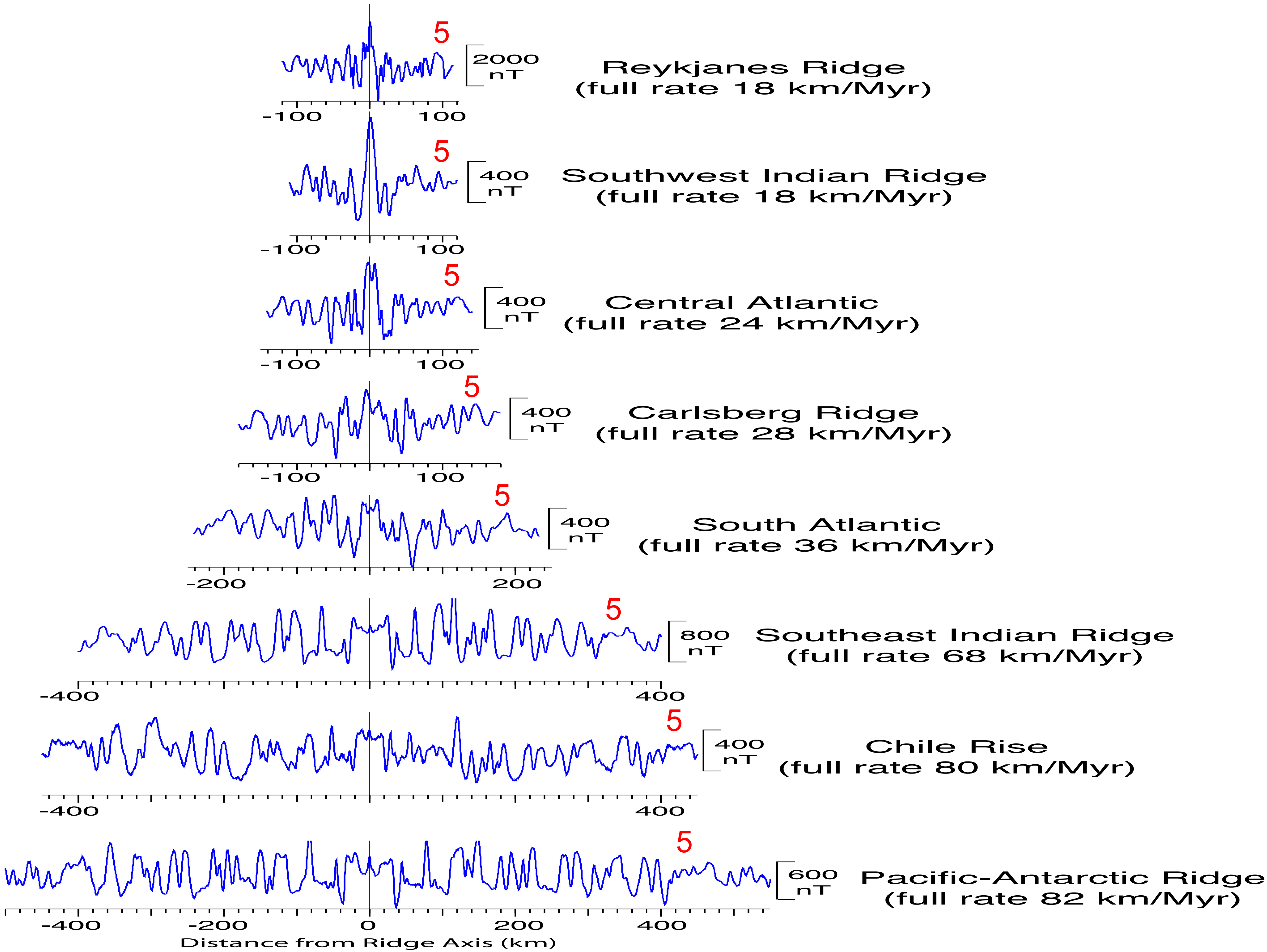
Intermediate
spreading rates




Slow
spreading rates




(Atwater)


5
2000 nT
Reykjanes Ridge
(full rate 18 km/Myr)
-100
100
5
400 nT
Southwest Indian Ridge
(full rate 18 km/Myr)
-100
100
5
400 nT
Central Atlantic
(full rate 24 km/Myr)
-100
100
5
400 nT
Carlsberg Ridge
(full rate 28 km/Myr)
-100
100
5
400 nT
South Atlantic
(full rate 36 km/Myr)
-200
200
5
800 nT
Southeast Indian Ridge
(full rate 68 km/Myr)
-400
400
5
400 nT
Chile Rise
(full rate 80 km/Myr)
-400
400
5
600 nT
Pacific-Antarctic Ridge
(full rate 82 km/Myr)
-400
-200
0
200
400
Distance from Ridge Axis (km)

The skewness of anomalies is dependent on both
1) the ambient inclination ($I_o$) and
2) the remanent inclination ($I_r$)

This makes computing the anomaly shape tricky because you have to know where it was formed.

On the other hand, with a little astute modeling, you can figure out the paleo-latitude

For a ridge striking East-West and currently at the North Pole ($I_o$ = 90):

Formed at the equator ($I_r$ = 0)

Formed at mid-latitude ($I_r$ = 45)

Formed at the North Pole ($I_r$ = 90)
(No drift)

A more recent timescale is by Cande and Kent (1992) (CK92).

CK92 went back and re-determined the anomaly spacings (for the first time since Heirtzler et al.) and applied a revised set of calibration points. A few modifications were made in 1995 (CK95).

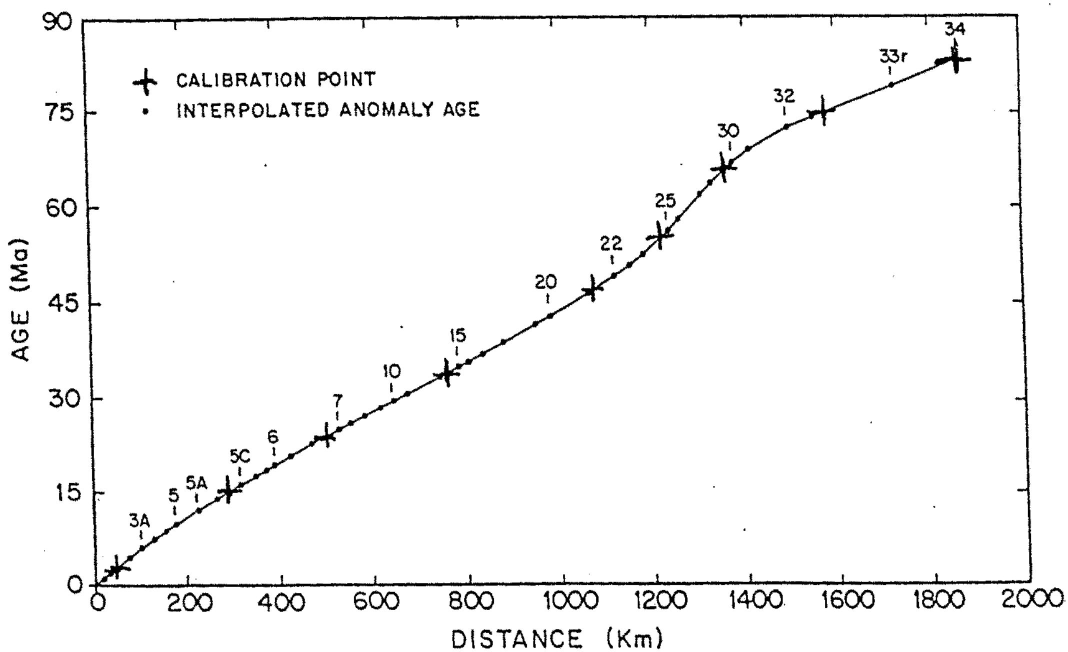



Fig. 27. Ages of magnetic anomalies (crosses) as determined by fitting a cubic spline approximation function to the calibration points (inverted triangles).

TABLE 5. Age Calibrations for Geomagnetic Polarity Time Scale

| Chron | South Atlantic distance,* km | Age, Ma |
|---|---|---|
| C2An(0.0) | 41.75 | 2.6 |
| C5Bn(0.0) | 290.17 | 14.8 |
| C6Cn.2r(0.0) | 501.55 | 23.8 |
| C13r(.14) | 759.49 | 33.7 |
| C21n(.33) | 1071.62 | 46.8 |
| C24r(.66) | 1221.20 | 55.0 |
| C29r(.3) | 1364.37 | 66.0 |
| C33n(.15) | 1575.56 | 74.5 |
| C34n(0.0) | 1862.32 | 83.0 |

*1.29 km subtracted to account for Central Anomaly offset.

# An "astronomical" timescale

Milankovich cycles:

Variations in the Earth's orbital parameters (eccentricity, tilt, precession) cause cyclical variations in the temperature of the earth's surface.

Periodicities of 23,000 – 40,000 – 100,000 and 400, 000 years.

These variations cause clear cycles in carbonate/clay ratios and turbidites in sedimentary sections. Can count them to get time durations with great accuracy.

In conjunction with magnetostratigraphic studies, can determine reversal times to an accuracy of 10,000 years – much better than from magnetic anomalies.

23 Ma

Presently, have done this systematically back to about ~~X~~ Ma – with more to come.