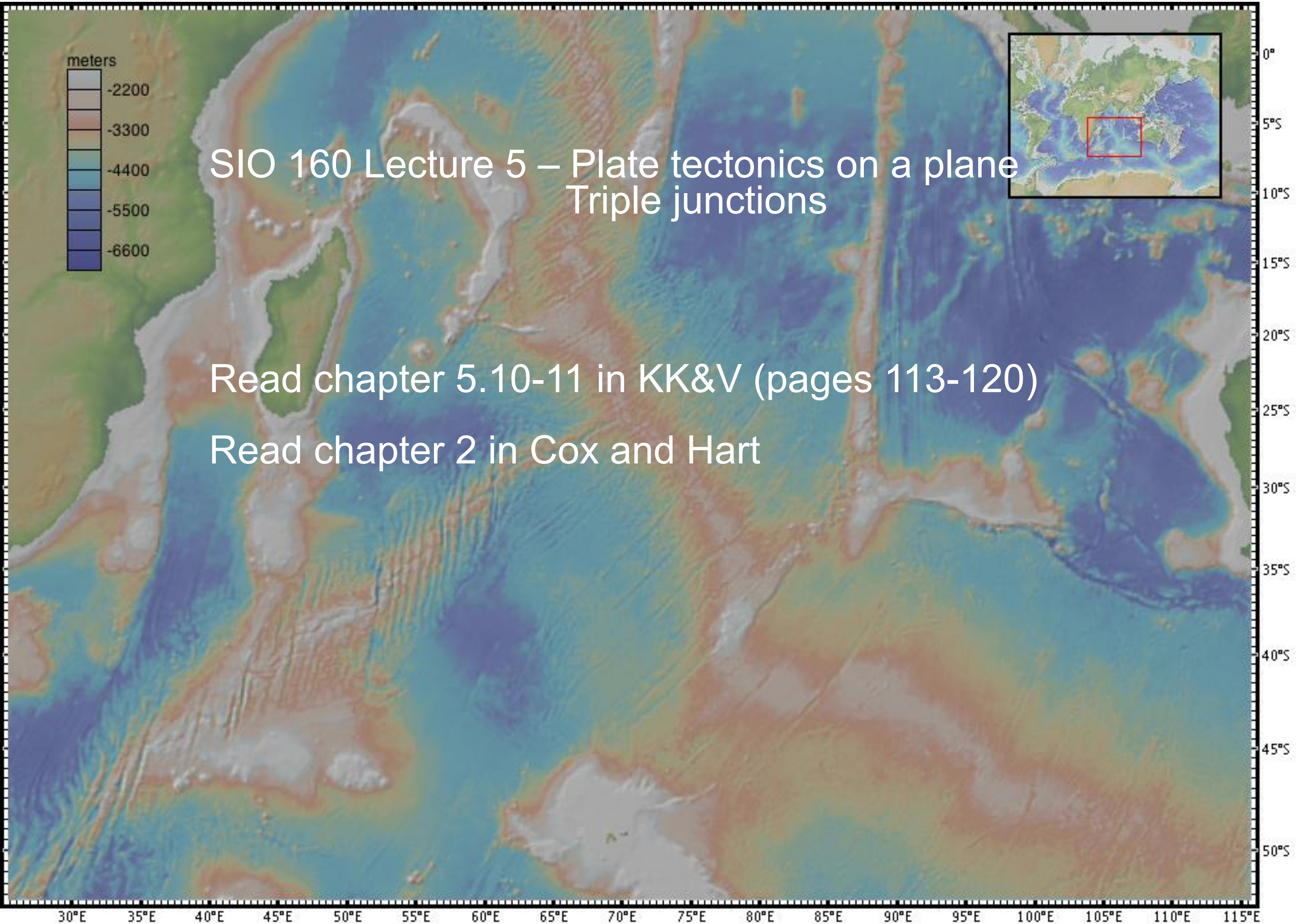
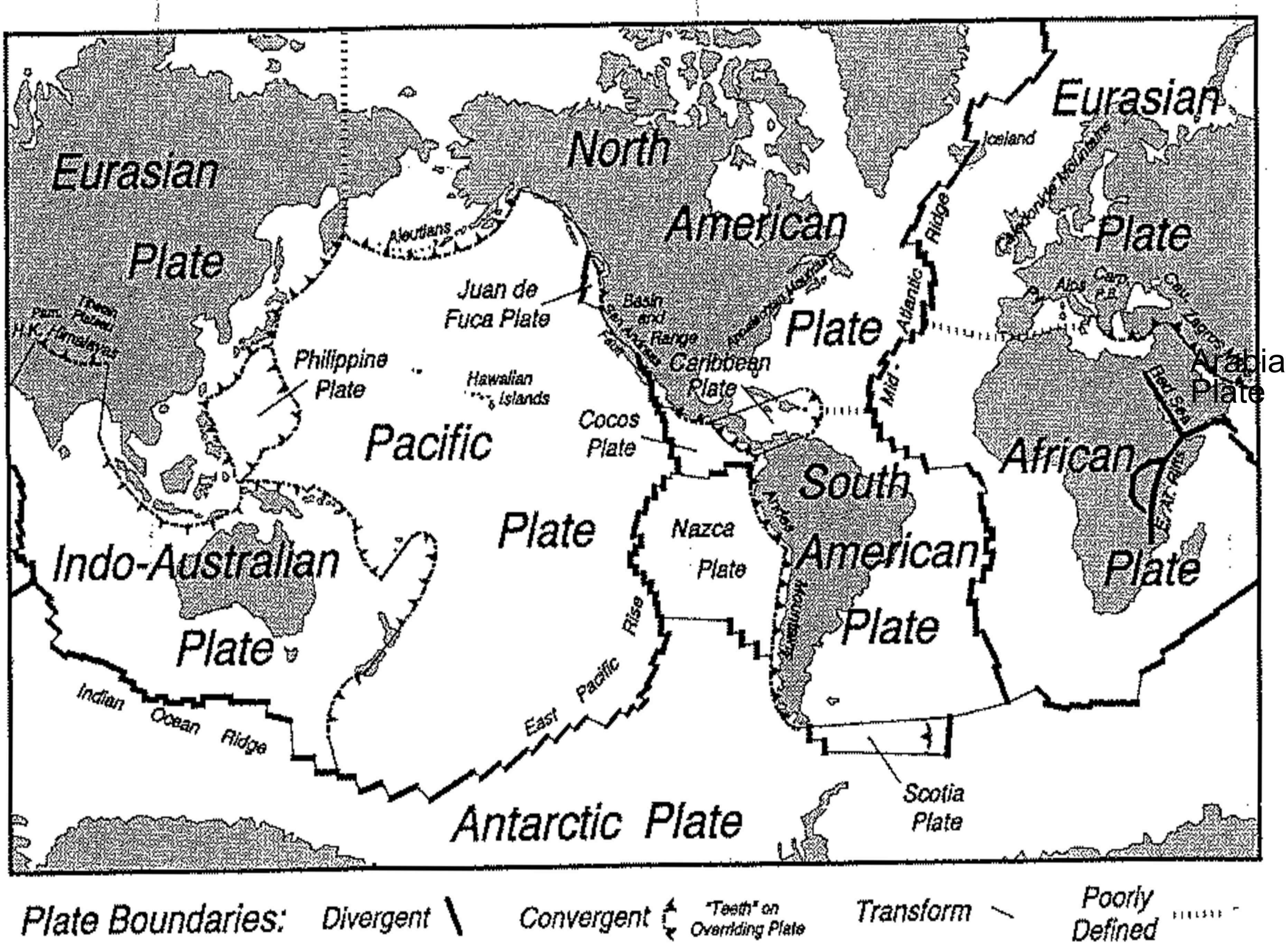
# SIO 160 Lecture 5 – Plate tectonics on a plane
# Triple junctions

Read chapter 5.10-11 in KK&V (pages 113-120)

Read chapter 2 in Cox and Hart

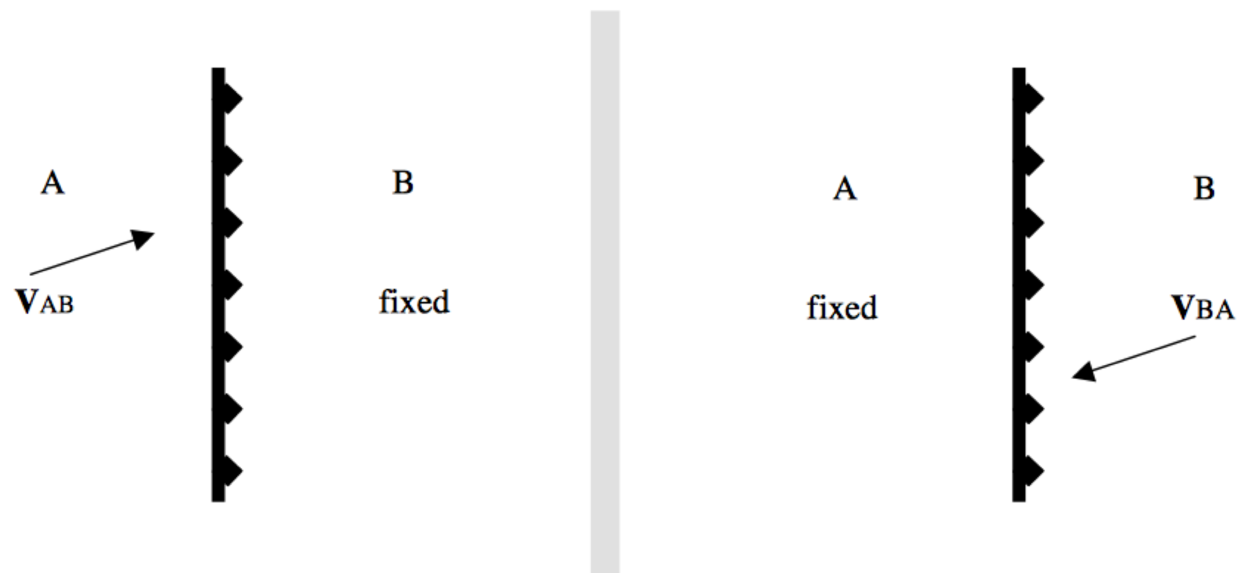




Eurasian Plate
North American Plate
Eurasian Plate
Iceland
Caledonide Mountains
Mid-Atlantic Ridge
Aleutians
Juan de Fuca Plate
Basin and Range
San Andreas Fault
Appalachian Mountains
Alps
Carp.
P.B.
Cau.
Zagros
Tibetan Plateau
Pam.
H.K. Himalayas
Philippine Plate
Hawaiian Islands
Caribbean Plate
Arabian Plate
Red Sea
Cocos Plate
Pacific Plate
African Plate
E. Af. Rifts
South American Plate
Andes
Nazca Plate
Indo-Australian Plate
East Pacific Rise
Indian Ocean Ridge
Scotia Plate
Antarctic Plate
Plate Boundaries:
Divergent
Convergent
"Teeth" on Overriding Plate
Transform
Poorly Defined

## Plate Motions on a Flat Earth

Plate tectonic theory describes the motions of rigid plates on a spherical earth. However, when considering the relative motions very close to the plate boundary, or at a triple junction, it is appropriate to use a flat earth approximation. We'll begin with the flat earth case and then move on to the spherical case. Consider 2 plates A and B, which have a subduction zone boundary between them such as the Nazca and South American plates. In this analysis all plate motions are relative so one can either consider plate B as fixed or plate A as fixed and draw the relative vector velocity between them as shown in the diagram below.



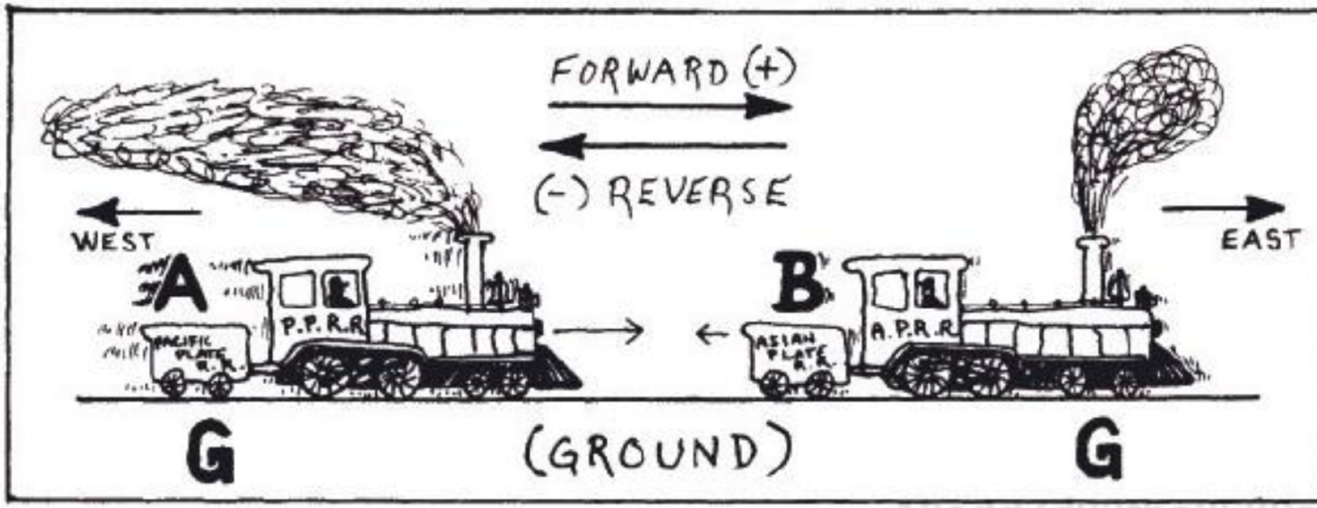

$\mathbf{V}_{AB}$ – velocity vector of plate A relative to plate B. $(= {}_{B}V_{A})$

$\mathbf{V}_{BA}$ – velocity vector of plate B relative to plate A. $(= {}_{A}V_{B})$

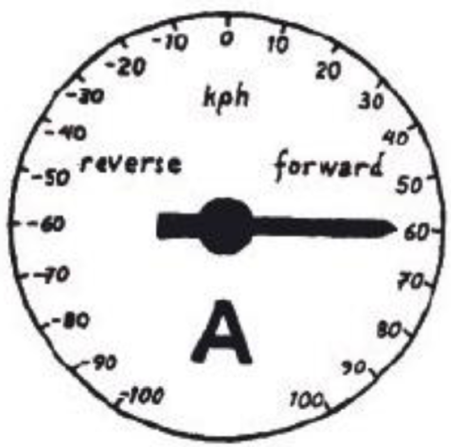
$$\mathbf{V}_{AB} = -\mathbf{V}_{BA}$$

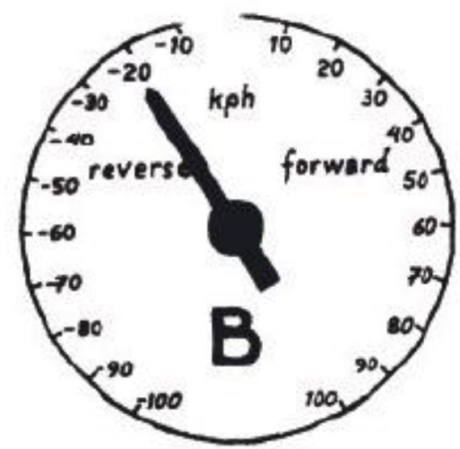
$$\mathbf{V}_{AB} = V_x i + V_y j$$

**Box 2-1.** The Velocity Line.

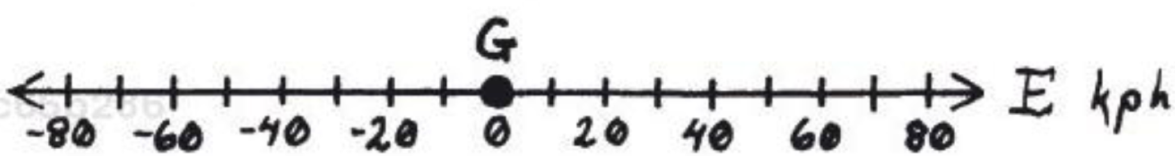




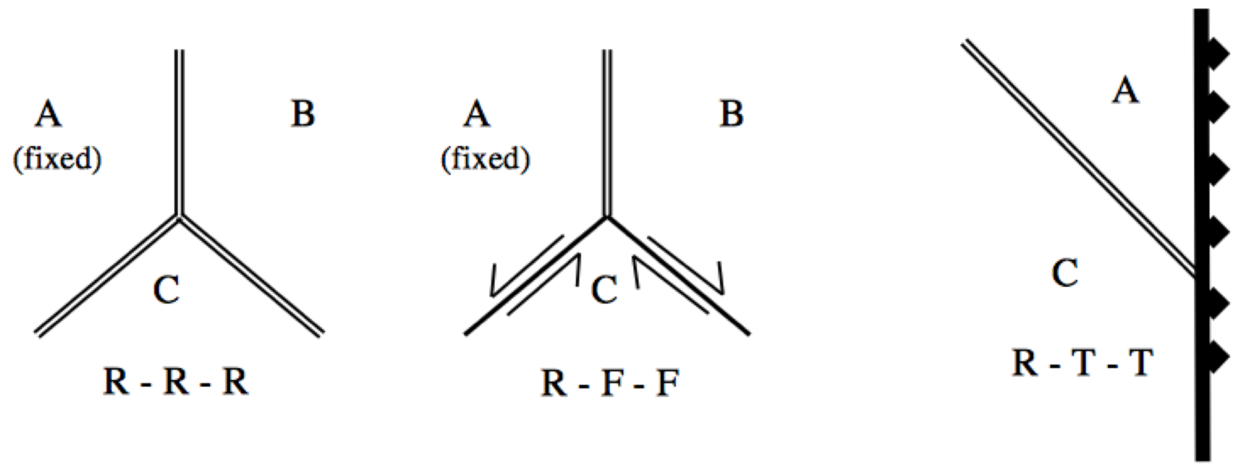




Train A is going east at 60 kph and train B is going west at 20 kph, both relative to the ground G. To keep your signs straight, observe that the speedometers read positive when the trains are going forward, which in this problem is toward the east. Eastward velocities will be regarded as positive and westward velocities as negative. The velocities of trains A and B and the ground G relative to each other may be represented by plotting three points **A, B,** and **G** on a **velocity line** as follows.



## Triple Junction

A triple junction is the intersection of three plate boundaries. The most common types of triple junctions are ridge-ridge-ridge (R-R-R), ridge-fault-fault (R-F-F), and ridge-trench-trench (R-T-T).




Each type of plate boundary has rules about relative velocities:

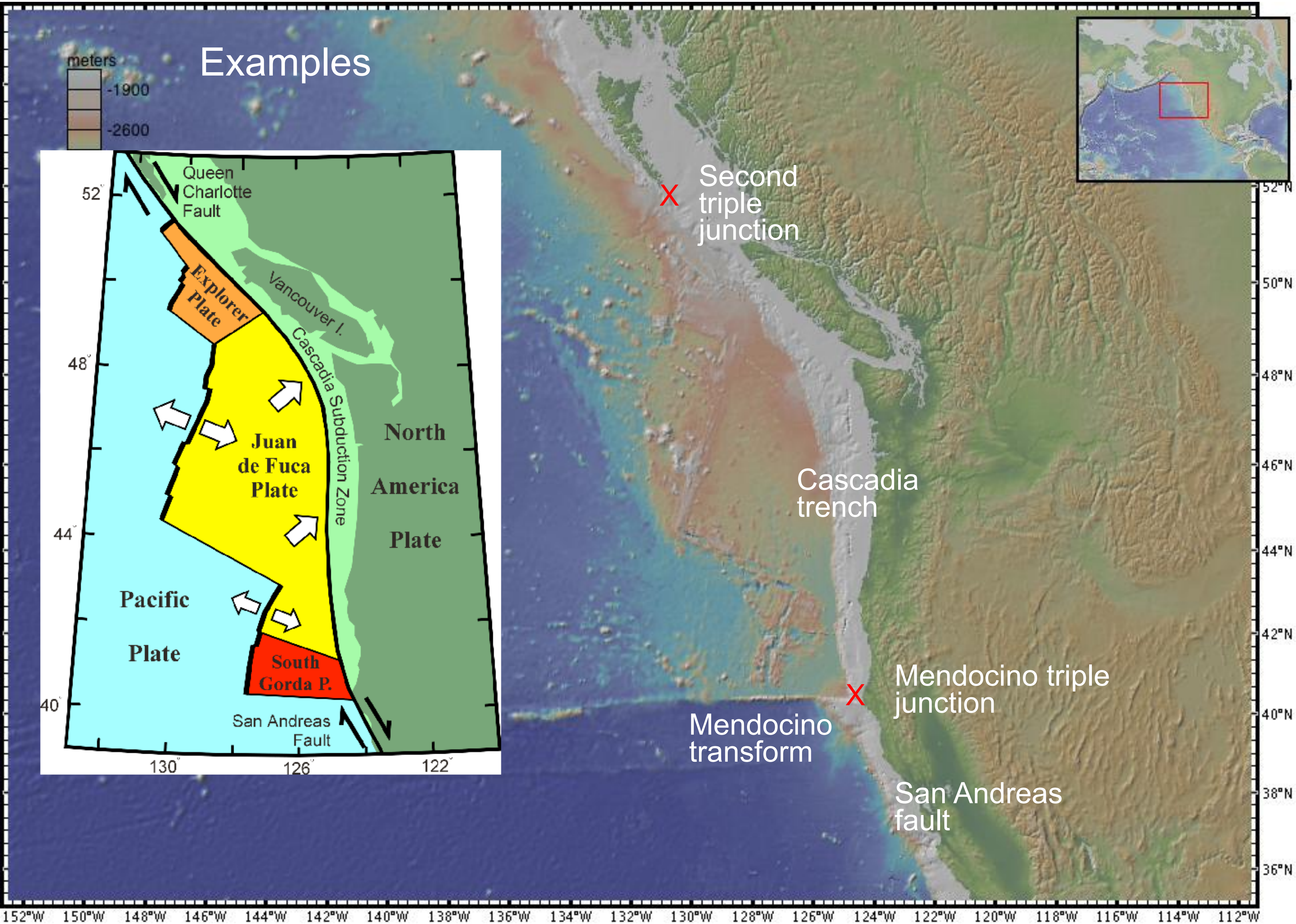
i) ridge - relative velocity must be divergent and is usually perpendicular to the ridge
ii) transform fault - relative velocity must be parallel to the fault
iii) trench - relative velocity must be convergent but no direction is preferred

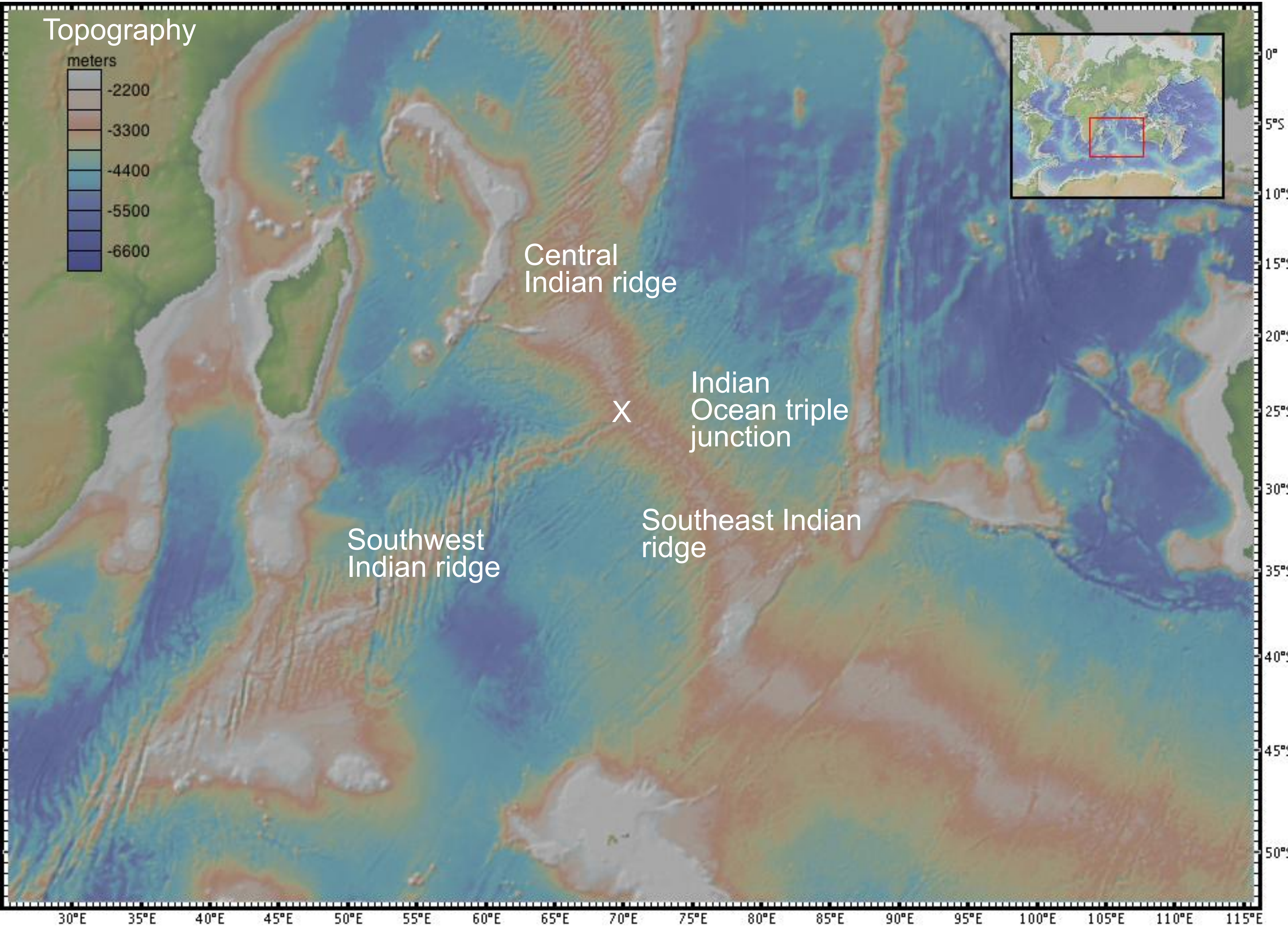
All triple junctions must satisfy a velocity condition such that the vector sum around the plate circuit is zero.

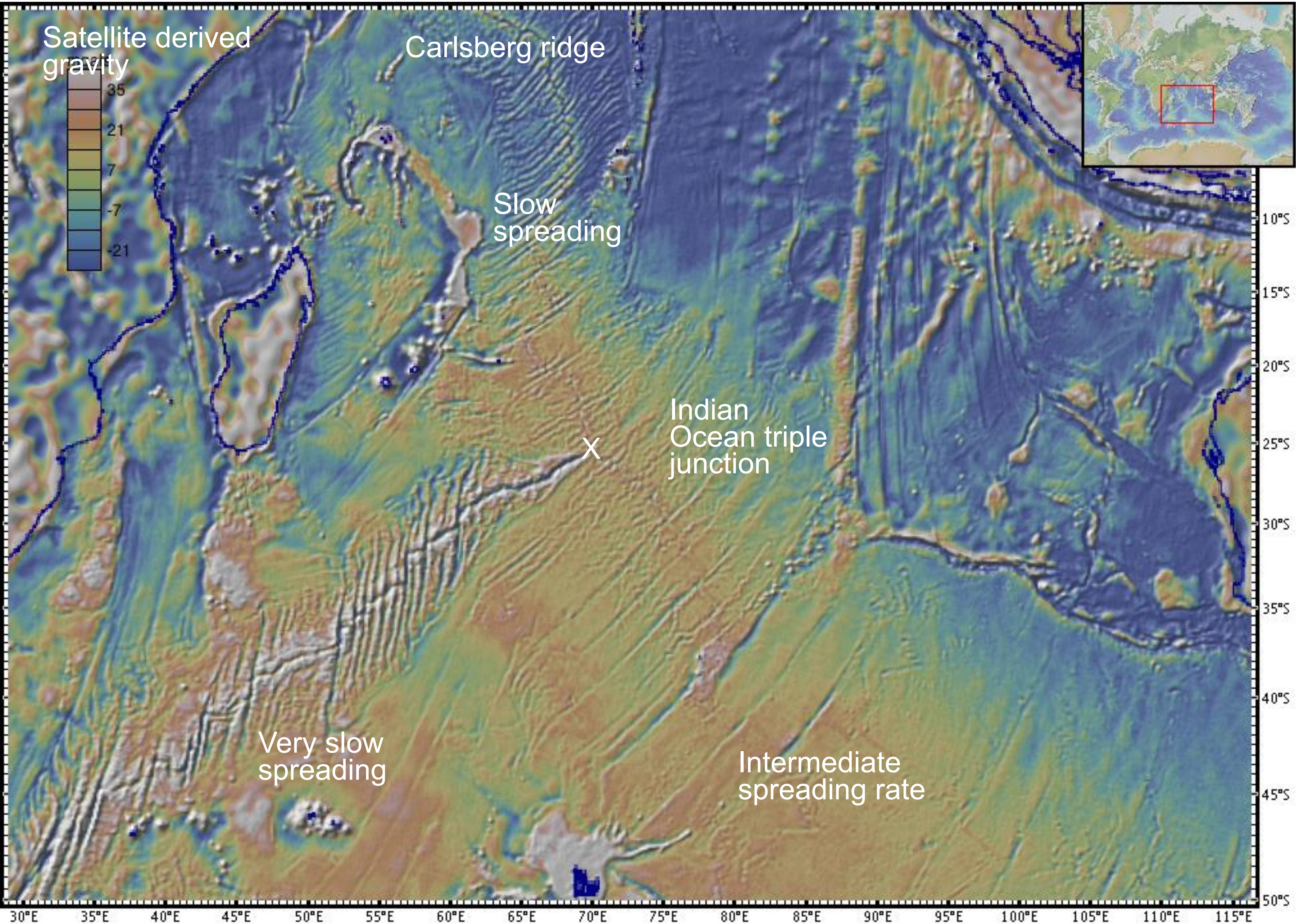
$$\mathbf{V}_{BA} + \mathbf{V}_{CB} + \mathbf{V}_{AC} = 0 \qquad (1)$$

In the real world we usually can map the geometry of the spreading ridges, transform faults and trenches but cannot always measure the relative velocities. The triple junction closure equation (1) can be used to solve for spreading velocities given the triple junction geometry, the rules, and at least one relative plate velocity.

# Examples


meters
-1900
-2600
Queen Charlotte Fault
Explorer Plate
Vancouver I.
Cascadia Subduction Zone
Juan de Fuca Plate
North America Plate
Pacific Plate
South Gorda P.
San Andreas Fault
52°
48°
44°
40°
130°
126°
122°
Second triple junction
Cascadia trench
Mendocino triple junction
Mendocino transform
San Andreas fault
52°N
50°N
48°N
46°N
44°N
42°N
40°N
38°N
36°N
152°W
150°W
148°W
146°W
144°W
142°W
140°W
138°W
136°W
134°W
132°W
130°W
128°W
126°W
124°W
122°W
120°W
118°W
116°W
114°W
112°W


Topography
meters
-2200
-3300
-4400
-5500
-6600
Central
Indian ridge
X
Indian
Ocean triple
junction
Southeast Indian
ridge
Southwest
Indian ridge
0°
5°S
10°S
15°S
20°S
25°S
30°S
35°S
40°S
45°S
50°S
30°E
35°E
40°E
45°E
50°E
55°E
60°E
65°E
70°E
75°E
80°E
85°E
90°E
95°E
100°E
105°E
110°E
115°E

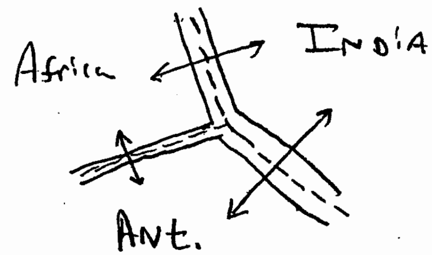

Satellite derived gravity
35
21
7
-7
-21
Carlsberg ridge
Slow spreading
Indian Ocean triple junction
X
Very slow spreading
Intermediate spreading rate
10°S
15°S
20°S
25°S
30°S
35°S
40°S
45°S
50°S
30°E
35°E
40°E
45°E
50°E
55°E
60°E
65°E
70°E
75°E
80°E
85°E
90°E
95°E
100°E
105°E
110°E
115°E

# Triple Junctions

16 Theoretical Types, 7 are observed

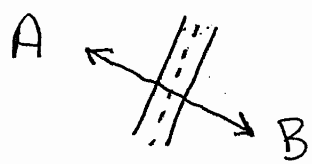
R = Ridge
F = transform Fault
T = Trench

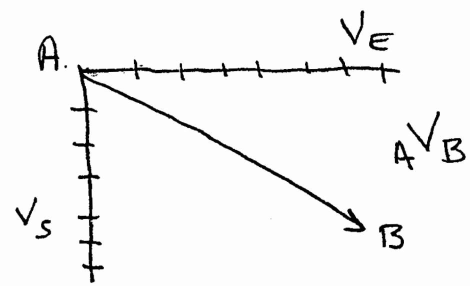
Example: RRR Central Indian Ocean




Velocity vector shows <u>relative</u> velocity of one plate to another

Velocity plane (velocity space)

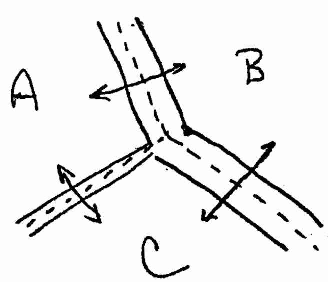


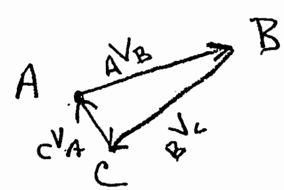




Velocity triangle:

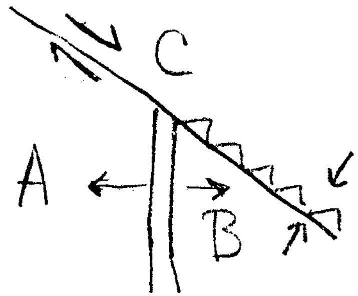
At a triple junction the relative velocity vectors of 3 plates form a closed triangle

$$ {}_AV_B + {}_BV_C + {}_CV_A = 0 $$



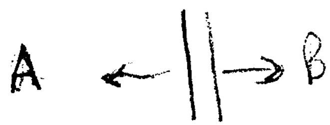



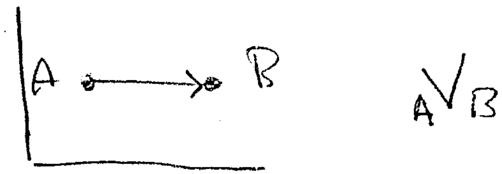
Consider a hypothetical triple junction with one of each basic type of plate boundary:



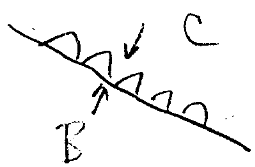

$${}_AV_B + {}_BV_C + {}_CV_A = 0$$

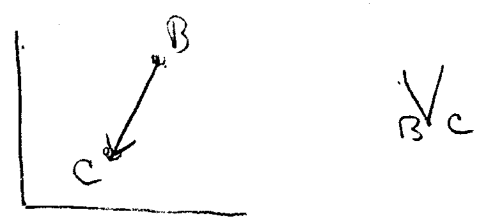
**Ridge**



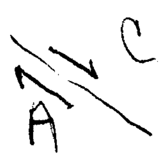




**Trench**



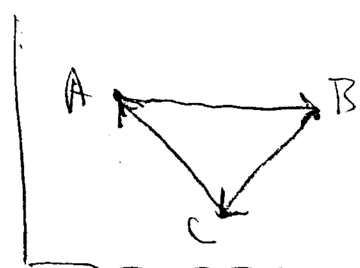




**Fault**



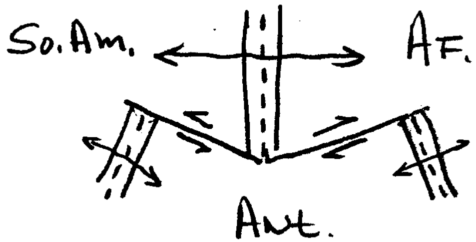


**Put it together**

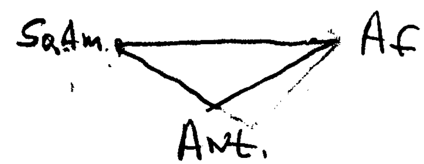


# Triple Junctions – More Examples

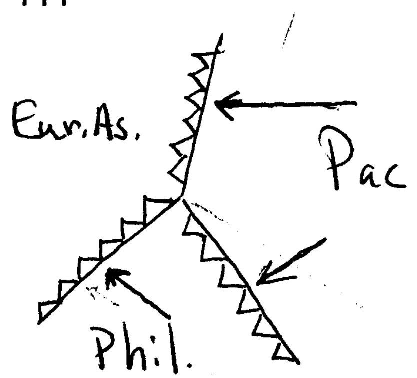
RFF



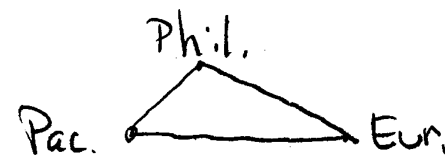

Bouvet Triple Junction



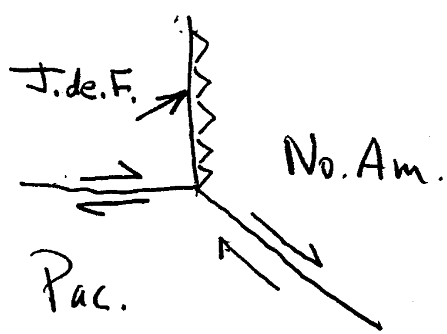

TTT



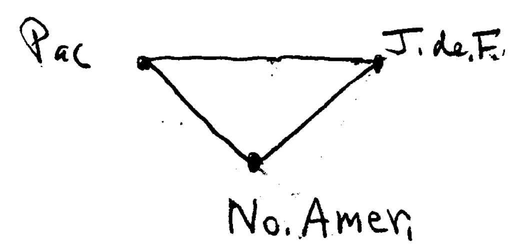

Japan Triple Junction

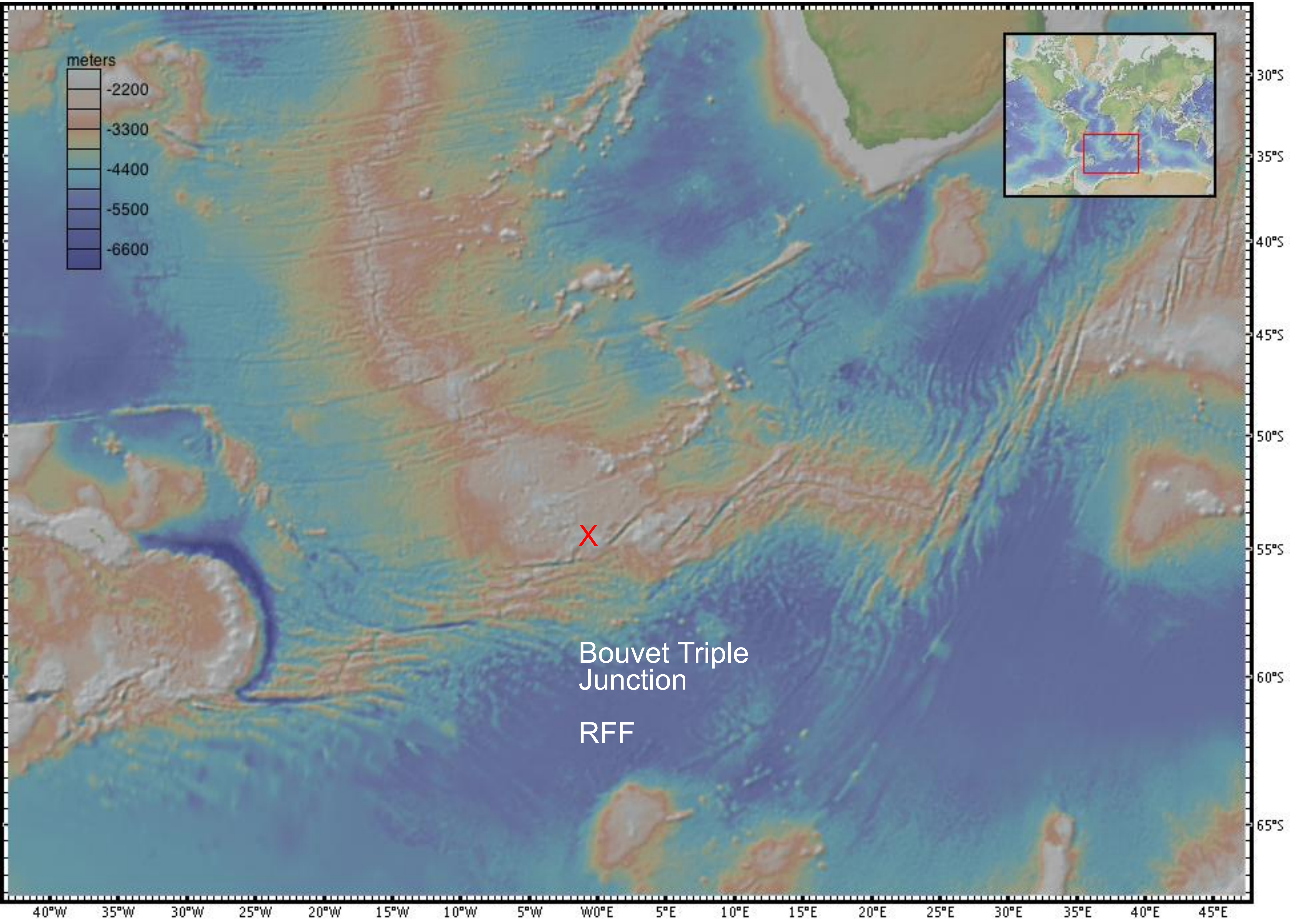



FFT

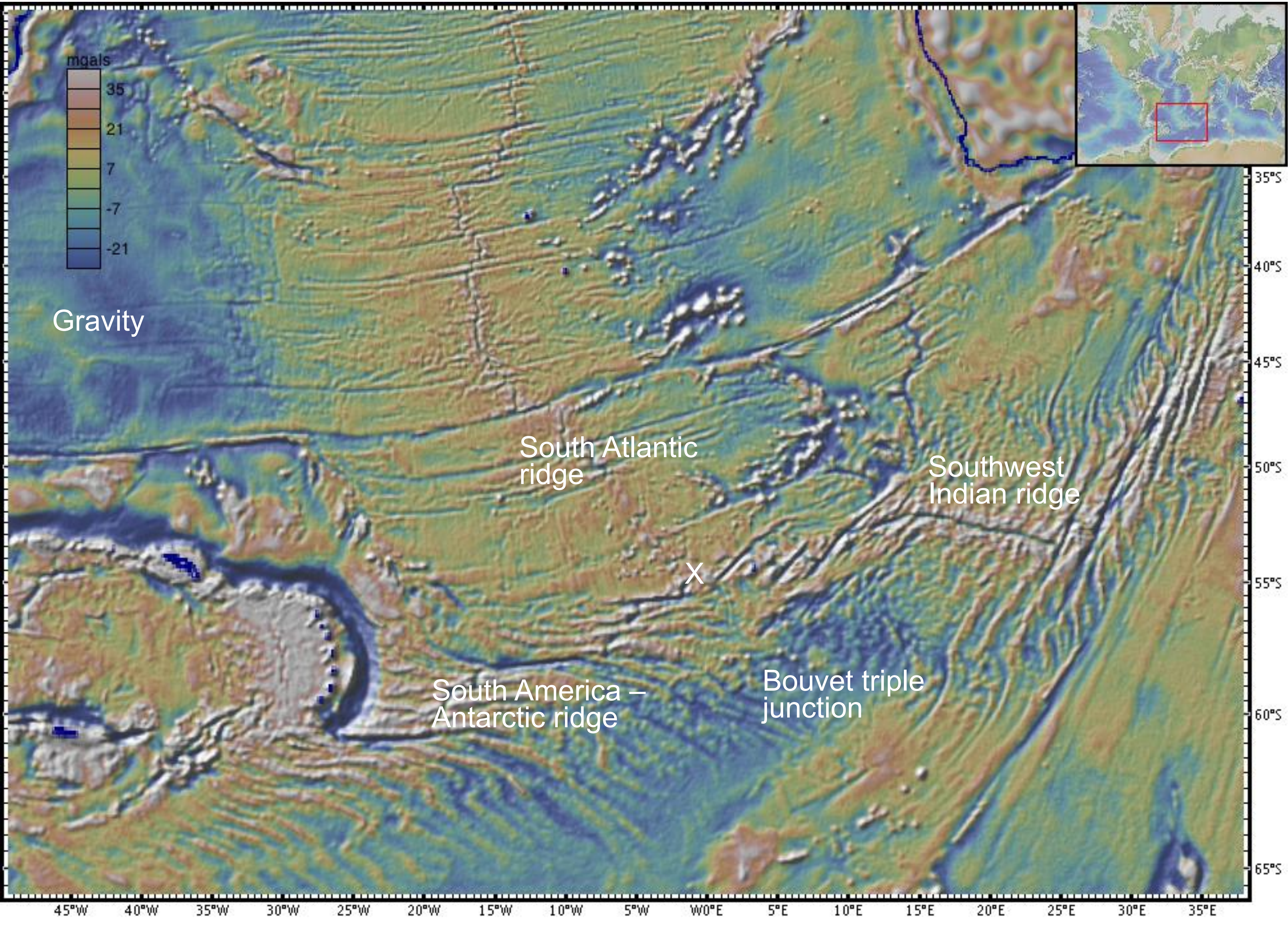



Mendocino Triple Junction

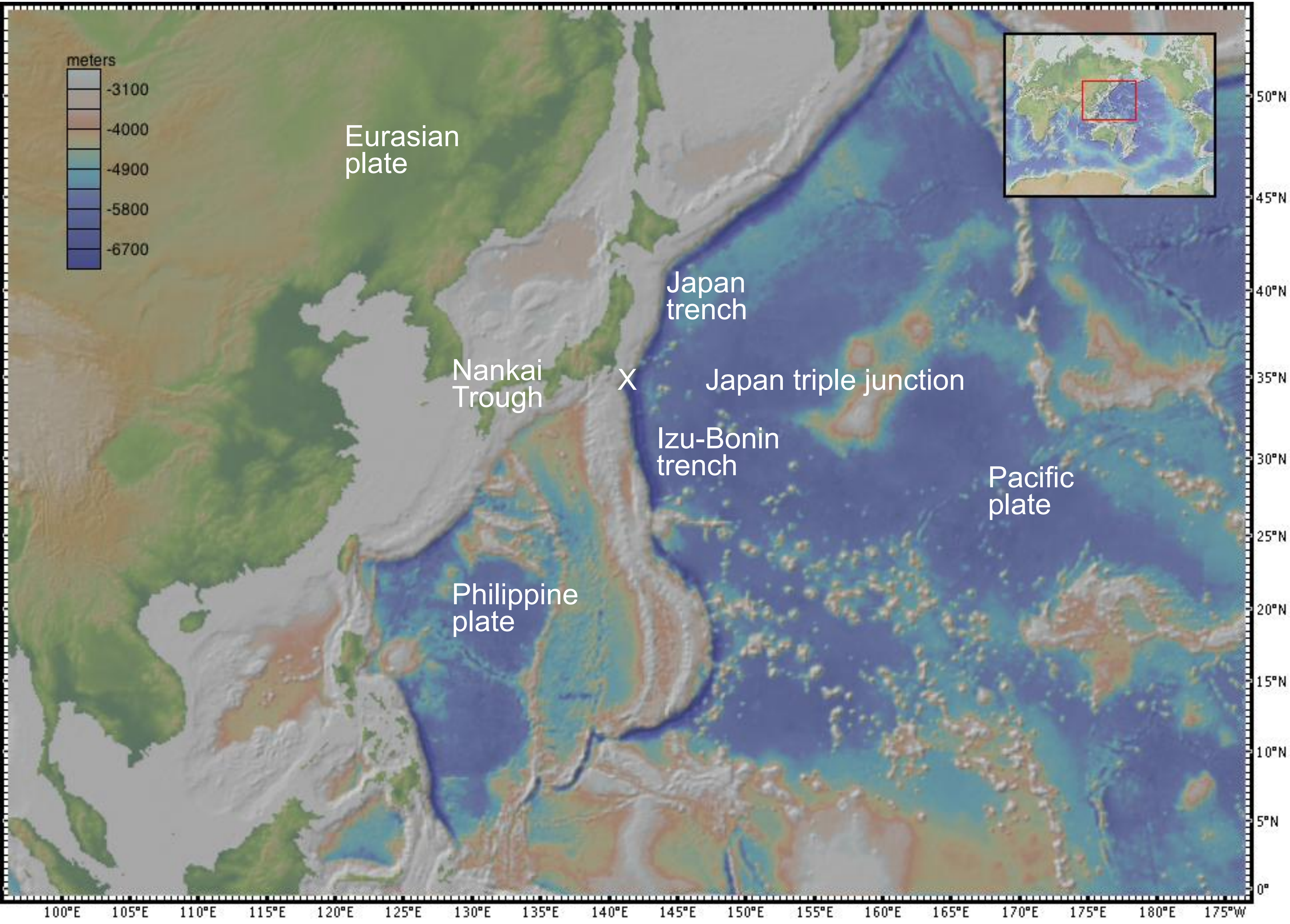




meters
-2200
-3300
-4400
-5500
-6600
X
Bouvet Triple Junction
RFF
30°S
35°S
40°S
45°S
50°S
55°S
60°S
65°S
40°W
35°W
30°W
25°W
20°W
15°W
10°W
5°W
W0°E
5°E
10°E
15°E
20°E
25°E
30°E
35°E
40°E
45°E



mgals
35
21
7
-7
-21
Gravity
South Atlantic ridge
Southwest Indian ridge
X
South America – Antarctic ridge
Bouvet triple junction
35°S
40°S
45°S
50°S
55°S
60°S
65°S
45°W
40°W
35°W
30°W
25°W
20°W
15°W
10°W
5°W
W0°E
5°E
10°E
15°E
20°E
25°E
30°E
35°E


meters
-3100
-4000
-4900
-5800
-6700
Eurasian plate
Japan trench
Nankai Trough
X
Japan triple junction
Izu-Bonin trench
Pacific plate
Philippine plate
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
10°N
5°N
0°
100°E
105°E
110°E
115°E
120°E
125°E
130°E
135°E
140°E
145°E
150°E
155°E
160°E
165°E
170°E
175°E
180°E
175°W

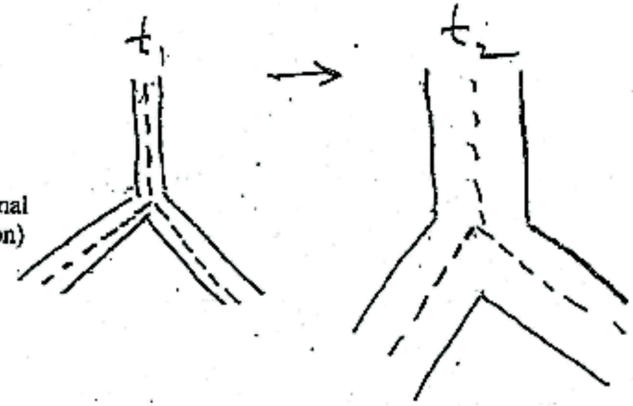
## Stability

Does the configuration stay the same over time?

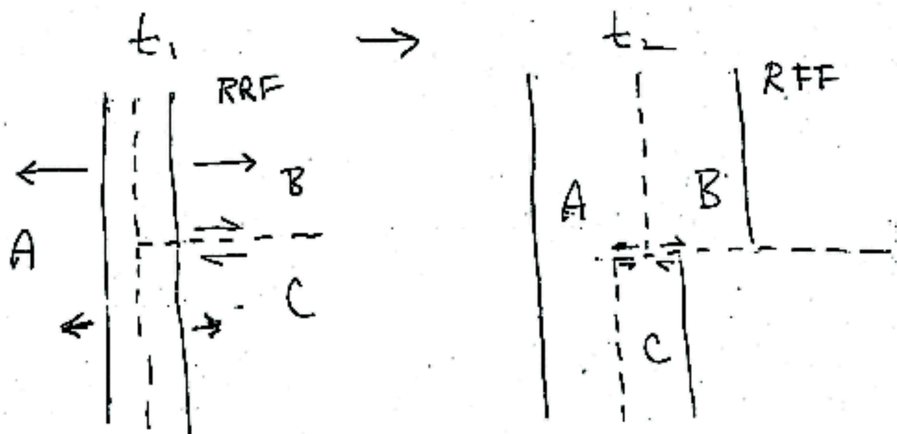
RRR

Stable

(if ridges are orthogonal to spreading direction)



RRF




Unstable

(unless the two ridges are orthogonal to each other)

1) RRR is usually stable
2) RRF is usually unstable

others: sometimes are, sometimes aren't

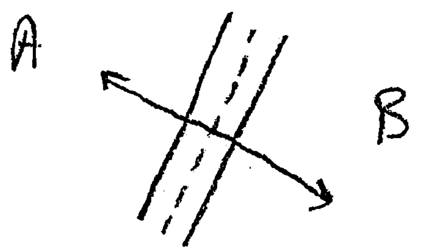
# Stability Analysis

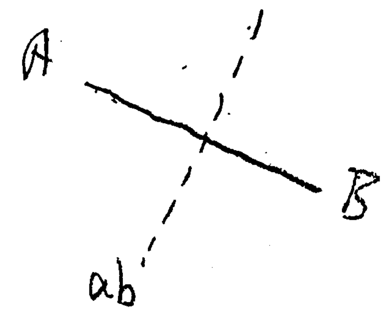
McKenzie & Morgan (1969)

## Velocity Line

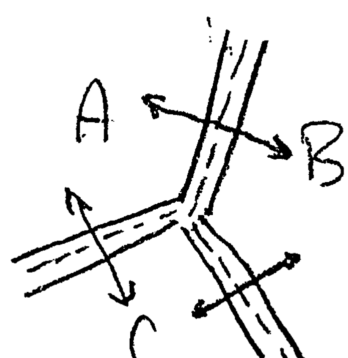
Locus of points on a plate boundary in velocity space where the triple junction can migrate relative to the two plates.

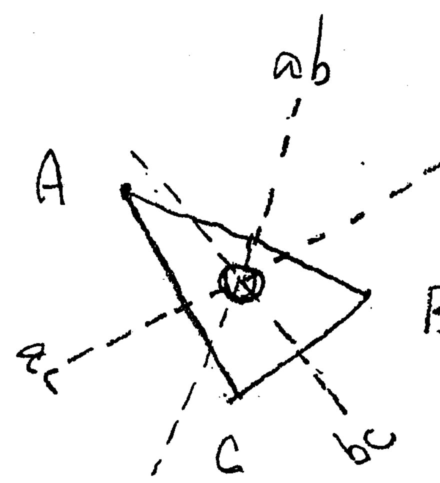
Consider a ridge AB:



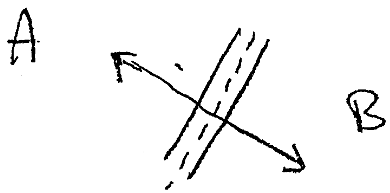

If the velocity lines intersect, then the triple junction is stable. The intersection point shows the motion of the triple junction relative to the three plates



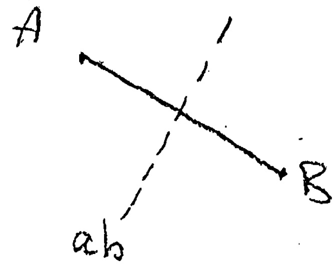



There are three types of velocity lines:

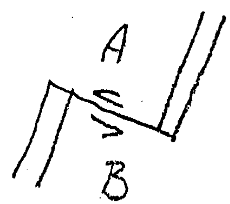
Ridge:



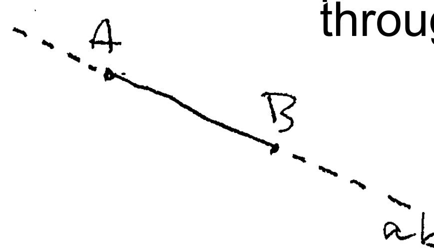

Velocity line is || to ridge and bisects the velocity vector



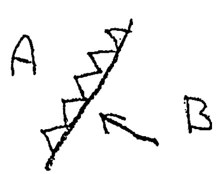

Fault:

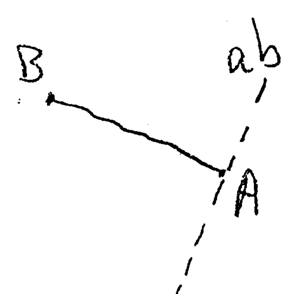



Velocity line passes through AB




Trench:

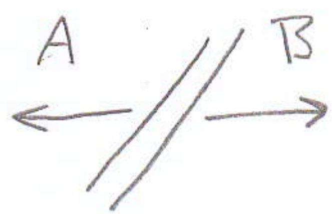


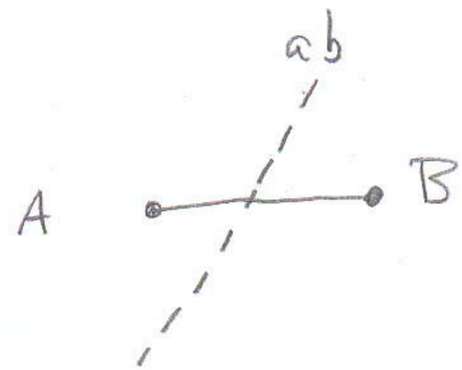




Velocity line passes through A is || to trench where A is the overriding plate

Special case: non-orthogonal spreading

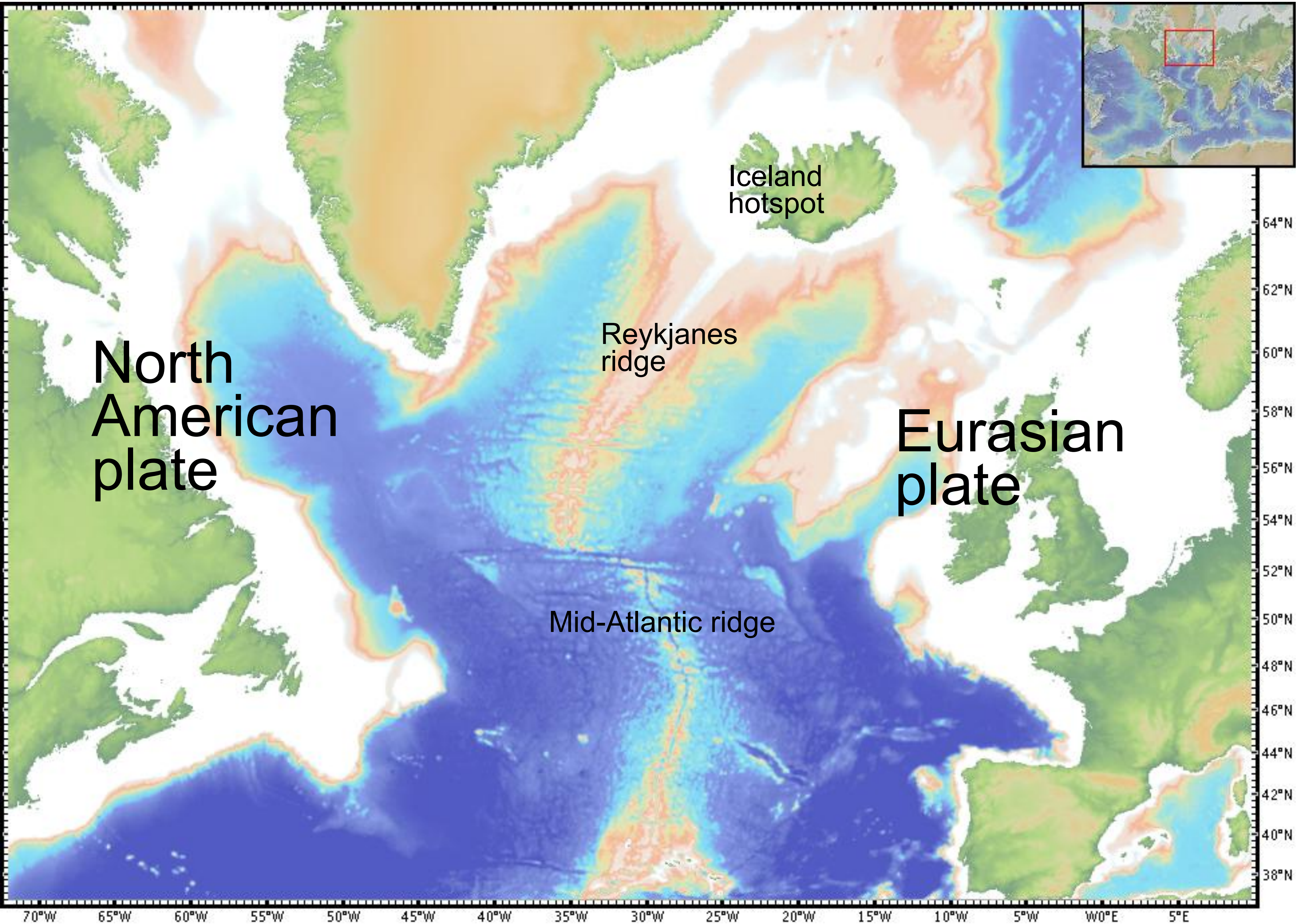
Cox & Hart   Ch. 2

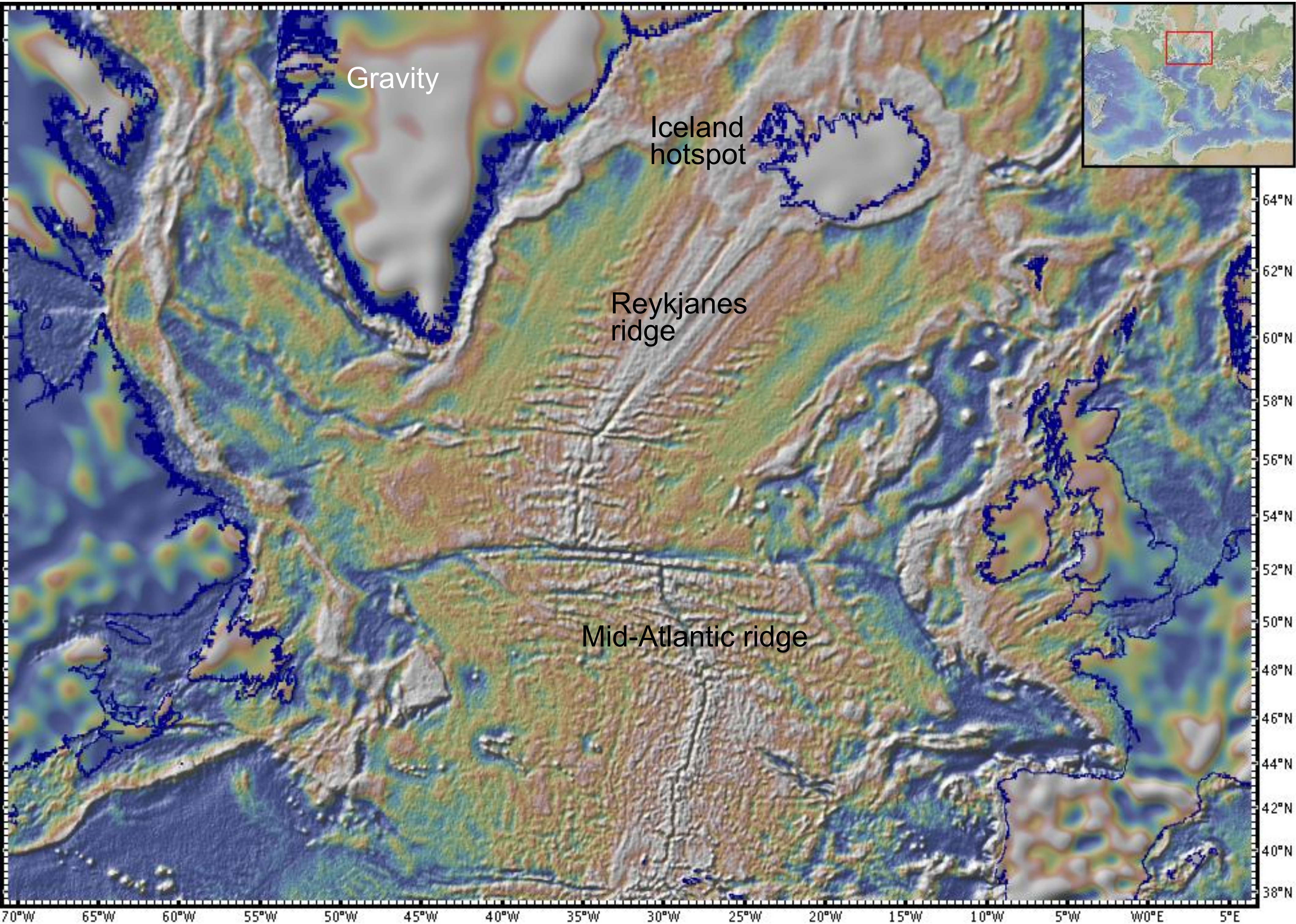


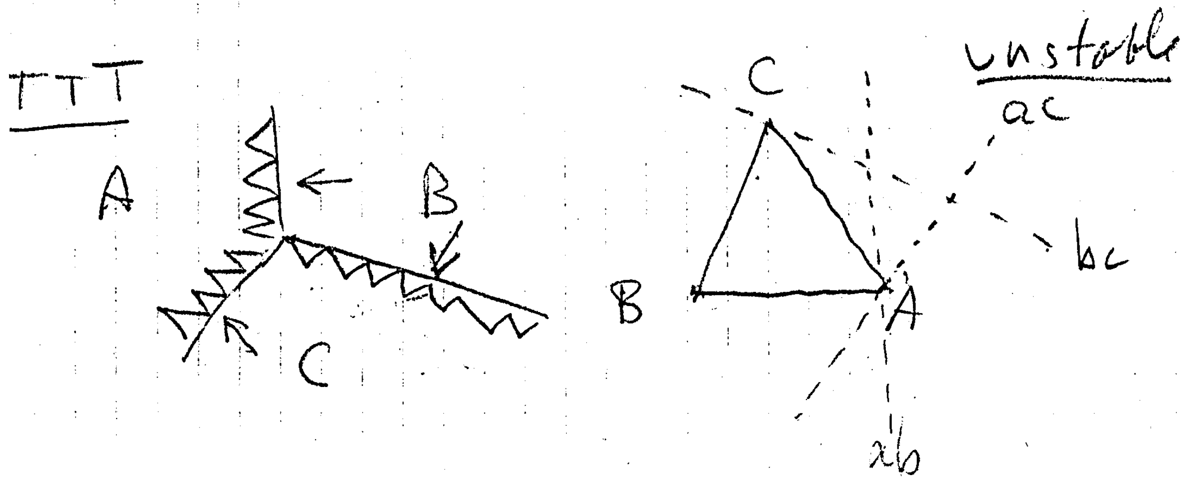

Note: The velocity line ab is parallel to the ridge and is not necessarily orthogonal to AB

Real world example: Reykjanes Ridge

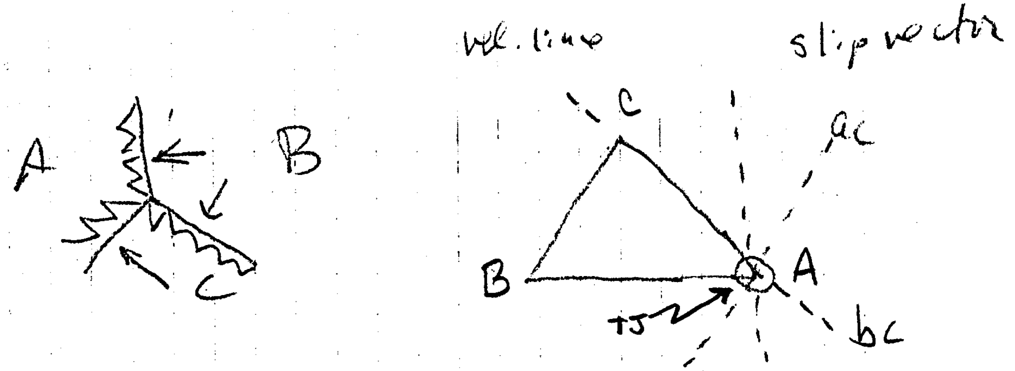

Iceland hotspot
Reykjanes ridge
North American plate
Eurasian plate
Mid-Atlantic ridge

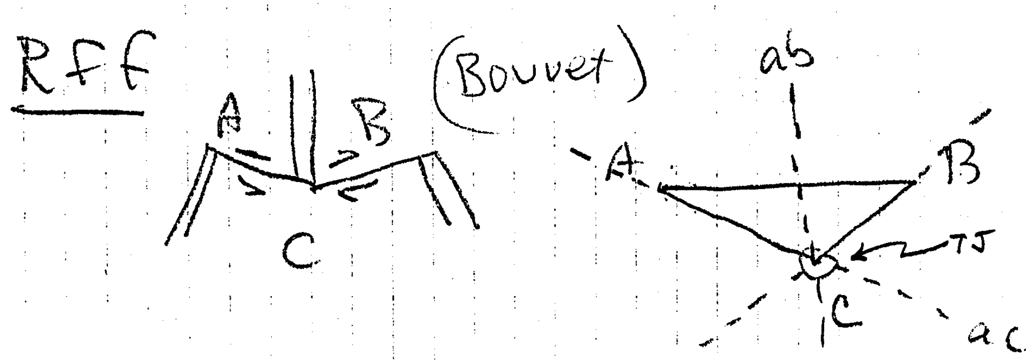

Gravity
Iceland
hotspot
Reykjanes
ridge
Mid-Atlantic ridge
64°N
62°N
60°N
58°N
56°N
54°N
52°N
50°N
48°N
46°N
44°N
42°N
40°N
38°N
70°W
65°W
60°W
55°W
50°W
45°W
40°W
35°W
30°W
25°W
20°W
15°W
10°W
5°W
W0°E
5°E

# Some more examples

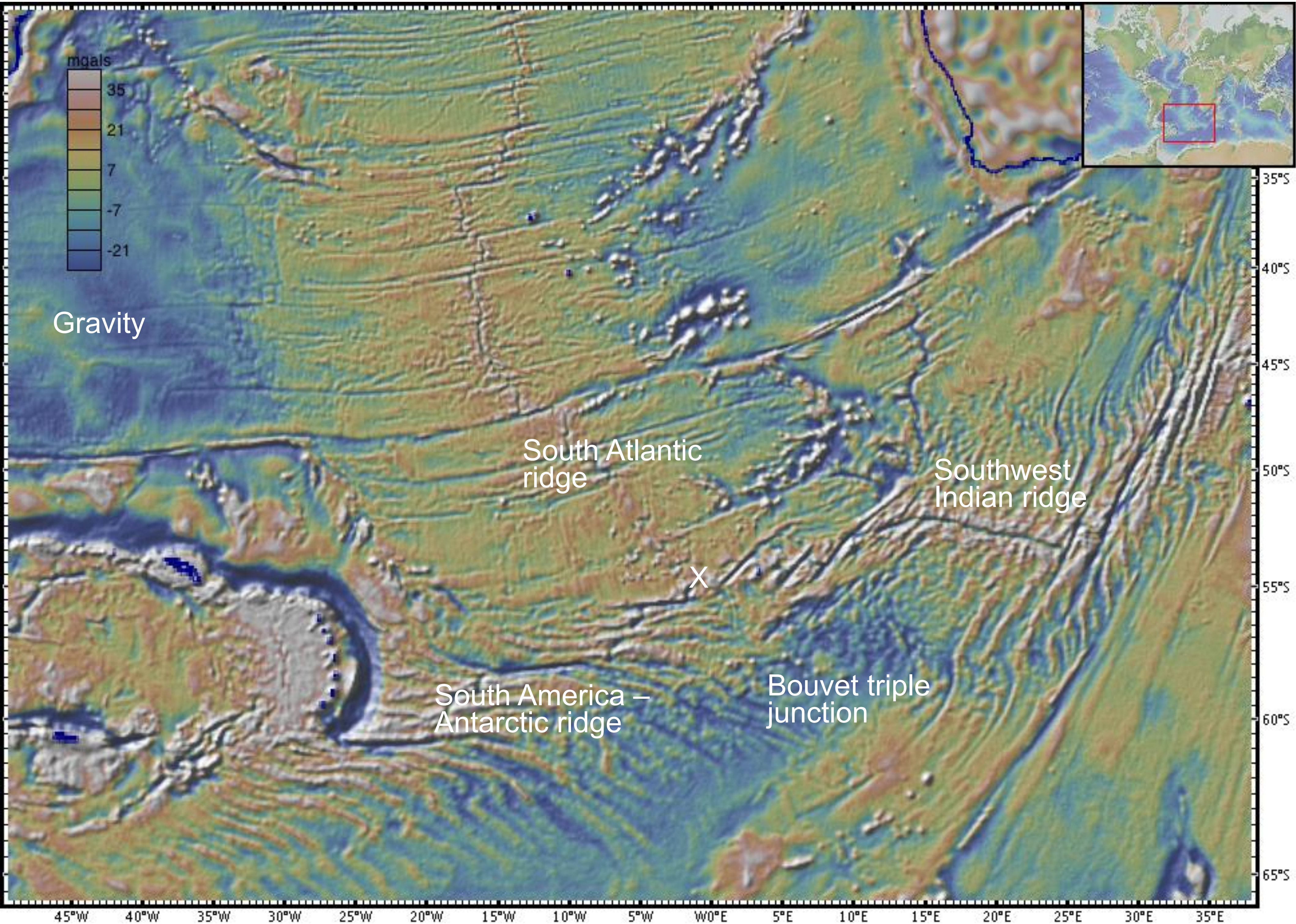



In general TTT is unstable.
However, it is stable if bc is parallel to CA

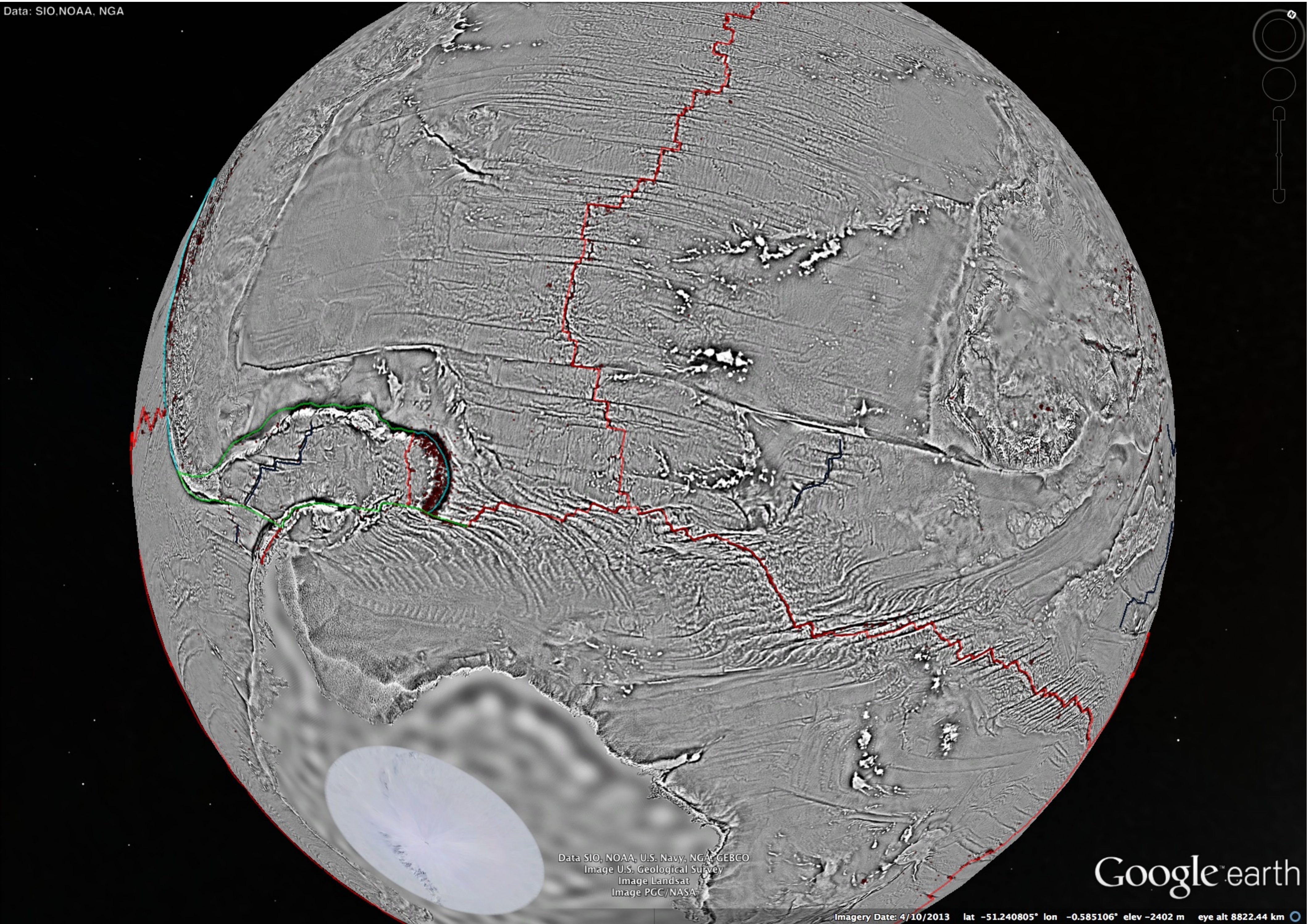


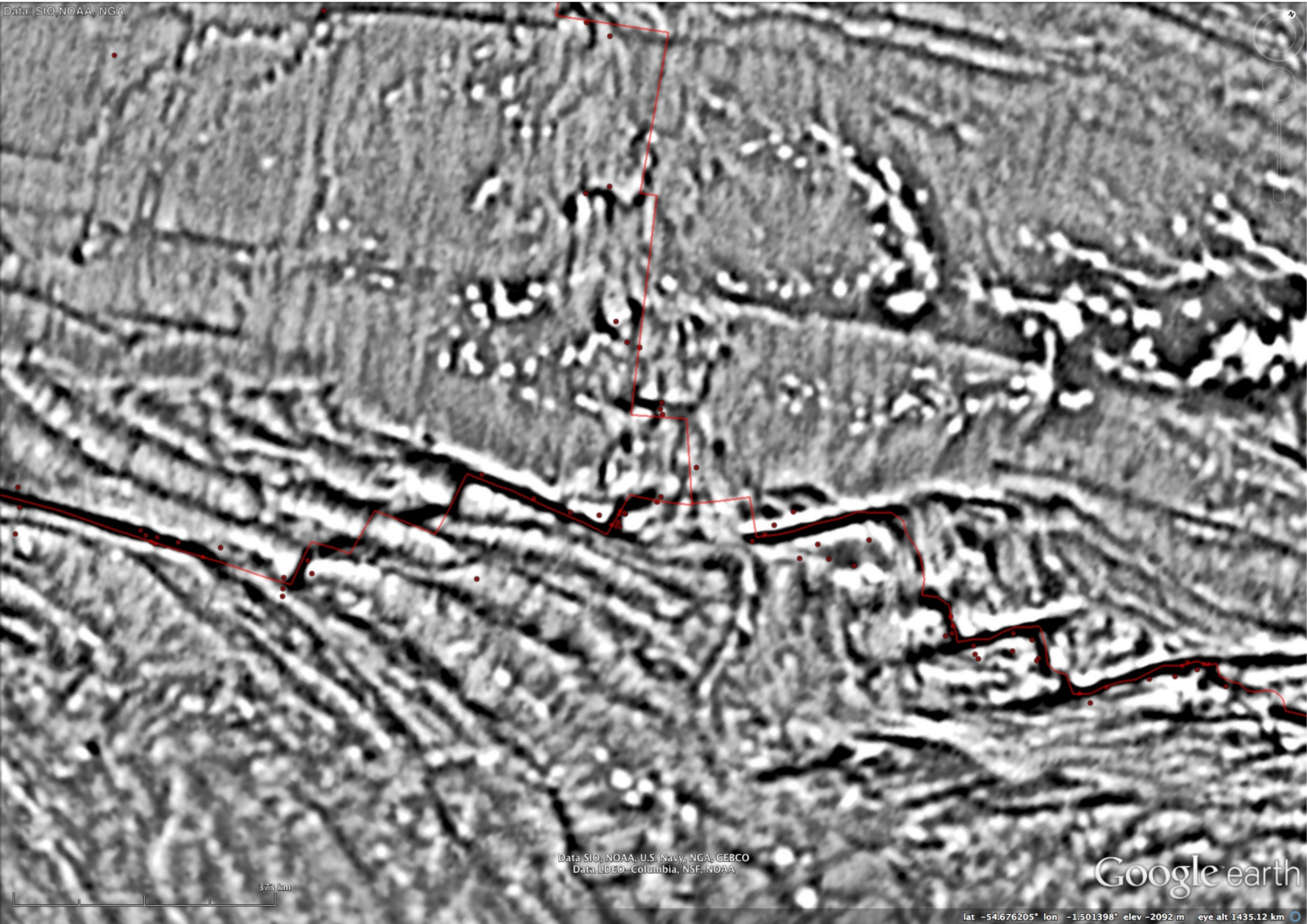

Stable, but can't continue forever.
May flip back and forth between RFF and RRR
or evolve by small ridge jumps


mgals
35
21
7
-7
-21
Gravity
South Atlantic ridge
Southwest Indian ridge
X
South America – Antarctic ridge
Bouvet triple junction
35°S
40°S
45°S
50°S
55°S
60°S
65°S
45°W
40°W
35°W
30°W
25°W
20°W
15°W
10°W
5°W
W0°E
5°E
10°E
15°E
20°E
25°E
30°E
35°E

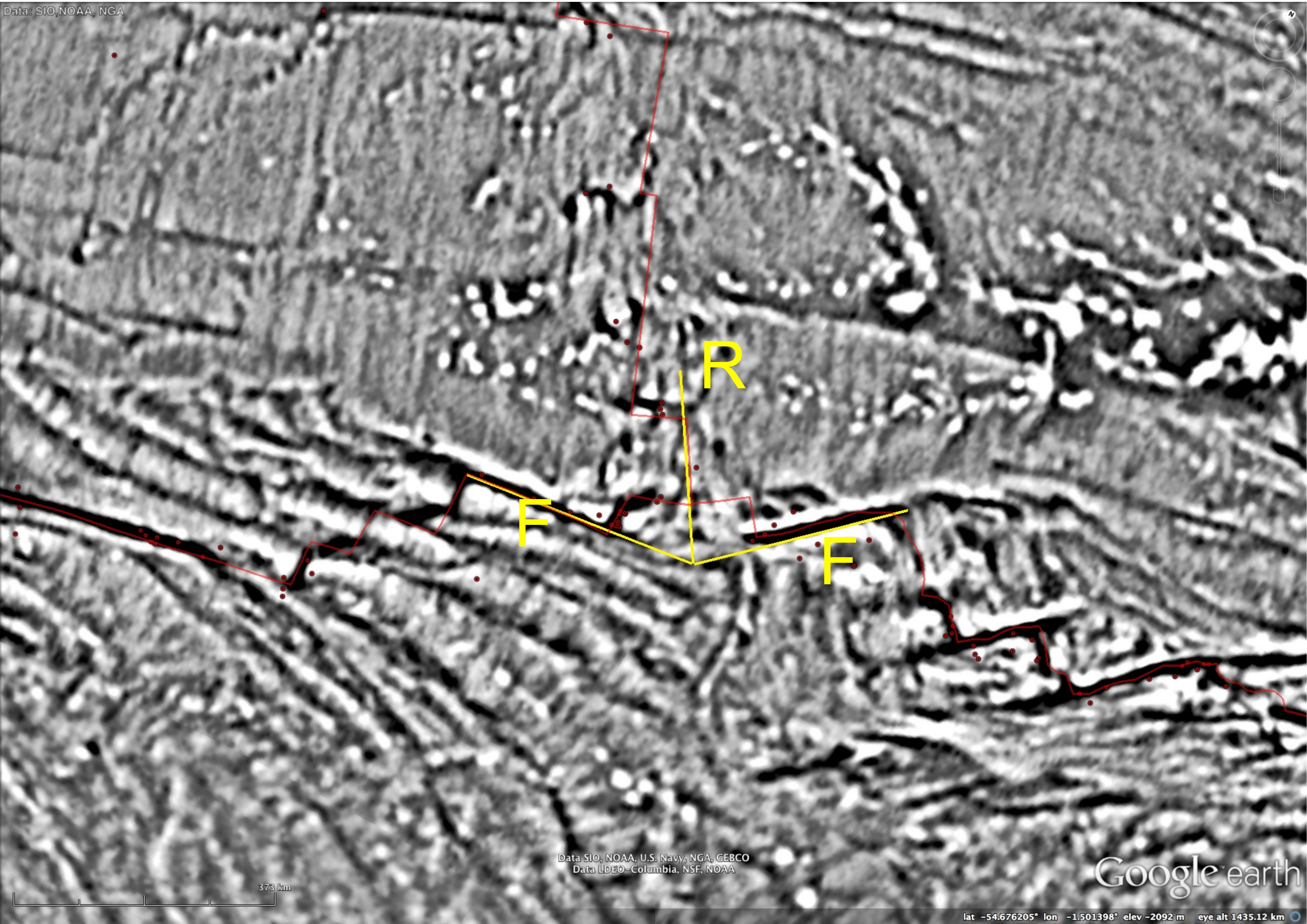
# Bouvet Triple Junction



# Bouvet Triple Junction



# Bouvet Triple Junction



Alaska
CANADA
NORTH
AMERICAN
PLATE
UNITED STATES
MEXICO
Yellowstone Hot Spot
Basin and Range Province
Gulf of California
PACIFIC
PLATE
ALEUTIAN
THRUST
QUEEN CHARLOTTE FAULT
JUAN DE FUCA PLATE
COBB HOT SPOT
JUAN DE FUCA RIDGE
GORDA PLATE
GORDA RIDGE
SAN ANDREAS FAULT
MENDOCINO FRACTURE ZONE
MURRAY FRACTURE ZONE
MOLOKAI FRACTURE ZONE
CLARION FRACTURE ZONE
HAWAII HOT SPOT
RIVERA F.
EAST PACIFIC RISE
CARIBBEAN PLATE
COCOS PLATE
MIDDLE AMERICA THRUST
Motagua Fault


USGS

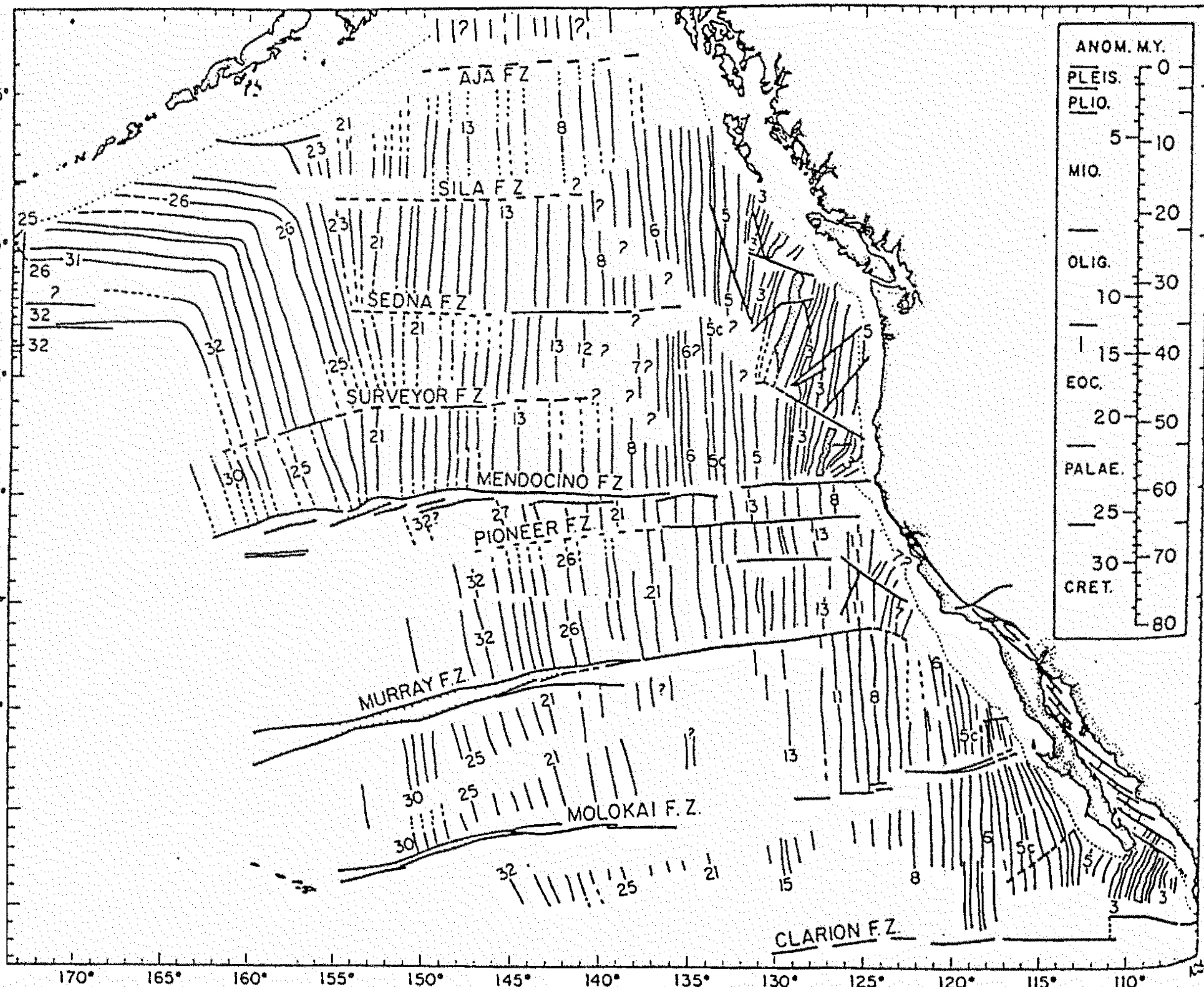
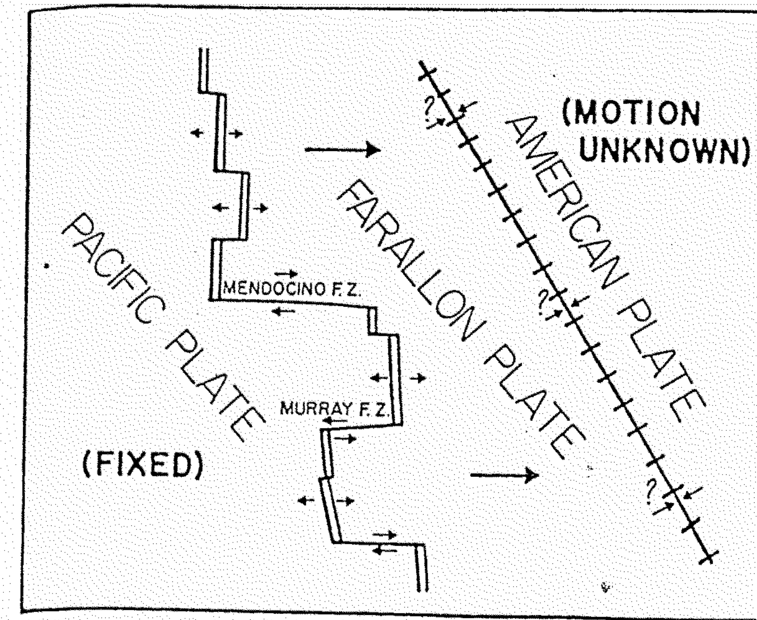


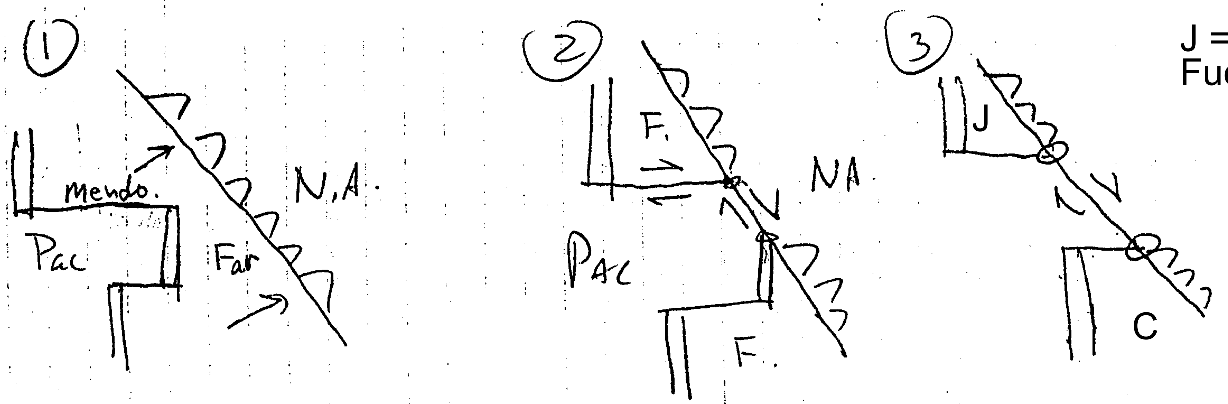

Figure 1. Magnetic anomalies in the northeast Pacific from Atwater and Menard (1970).




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

Atwater (1970)

## Pacific – Farallon – North America



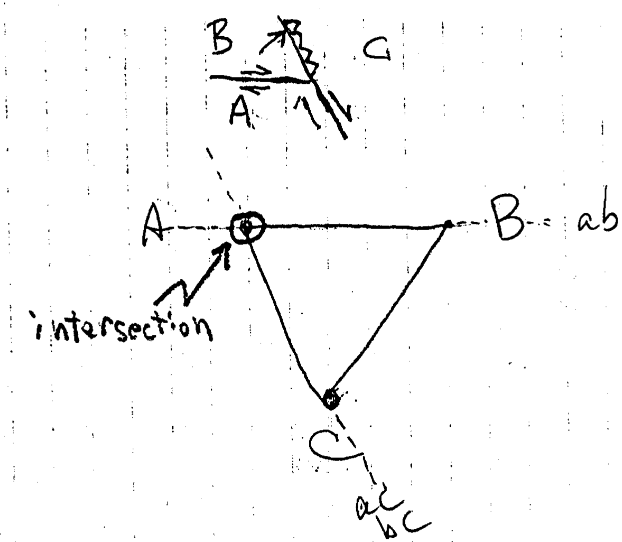

J = Juan de Fuca plate

C = Cocos plate

After collision, 2 triple junctions: Mendocino (TFF) and Rivera

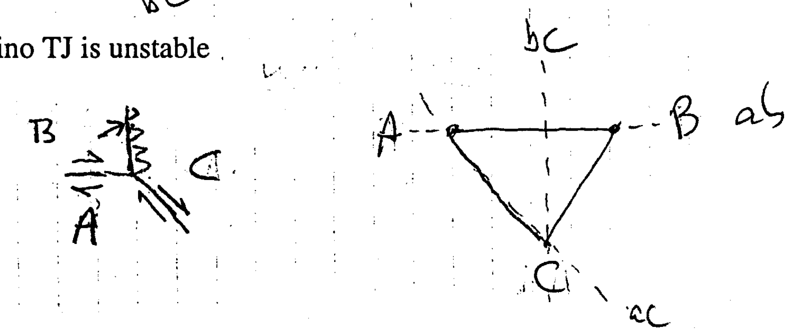
Rivera flips between TRF and TFF

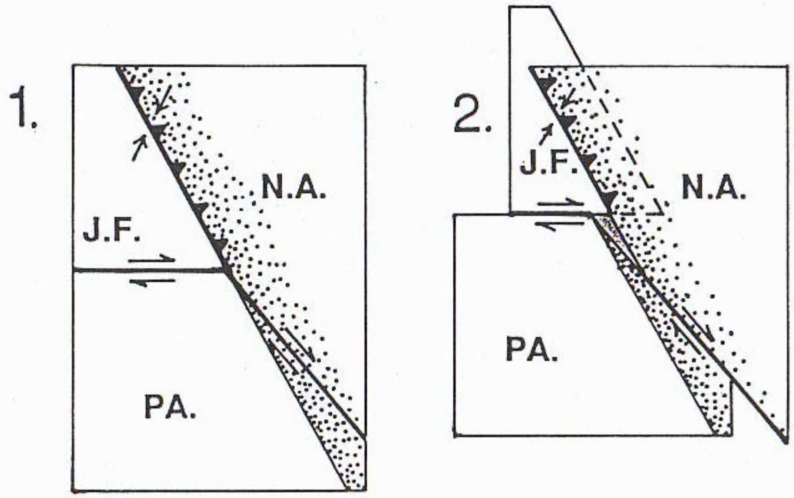
Mendocino




TJ migrates NW relative to No. Amer. (C)

In reality, Mendocino TJ is unstable






Approximation of the present Mendocino junction. The San Andreas fault and the Cascadia trench are not colinear. When the plates move, the triangular gap that appears at the junction (red triangle) must be accommodated by the surrounding regions. This junction is unstable.

Which is why there is a fault running through Berkeley Stadium

(The Hayward fault)

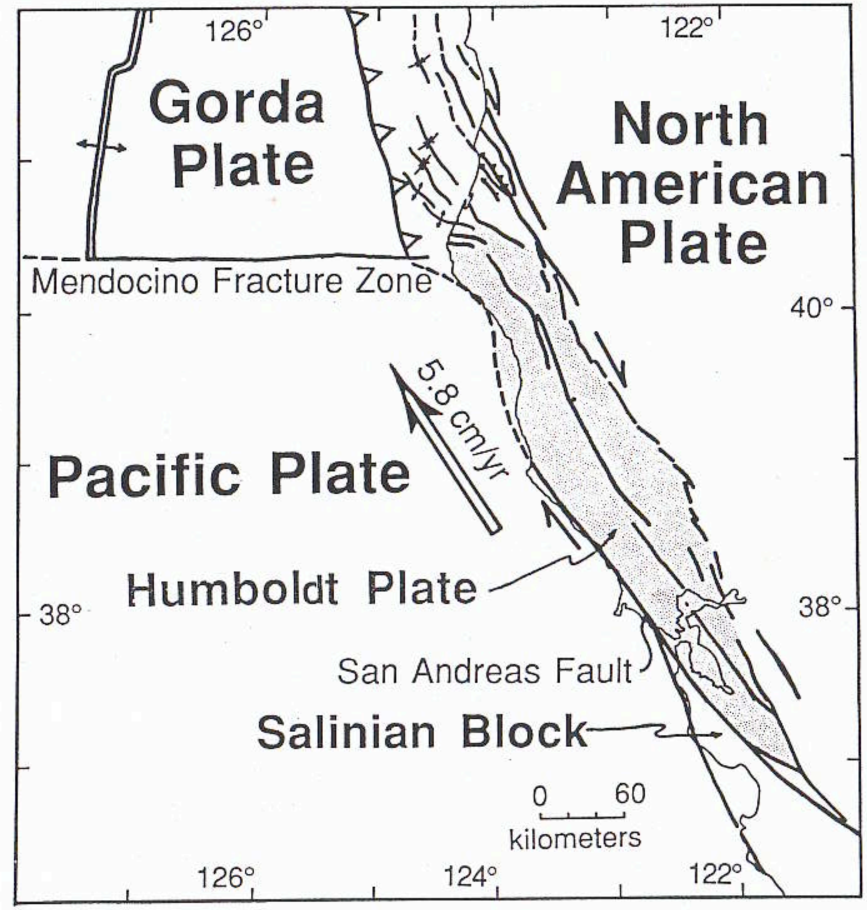
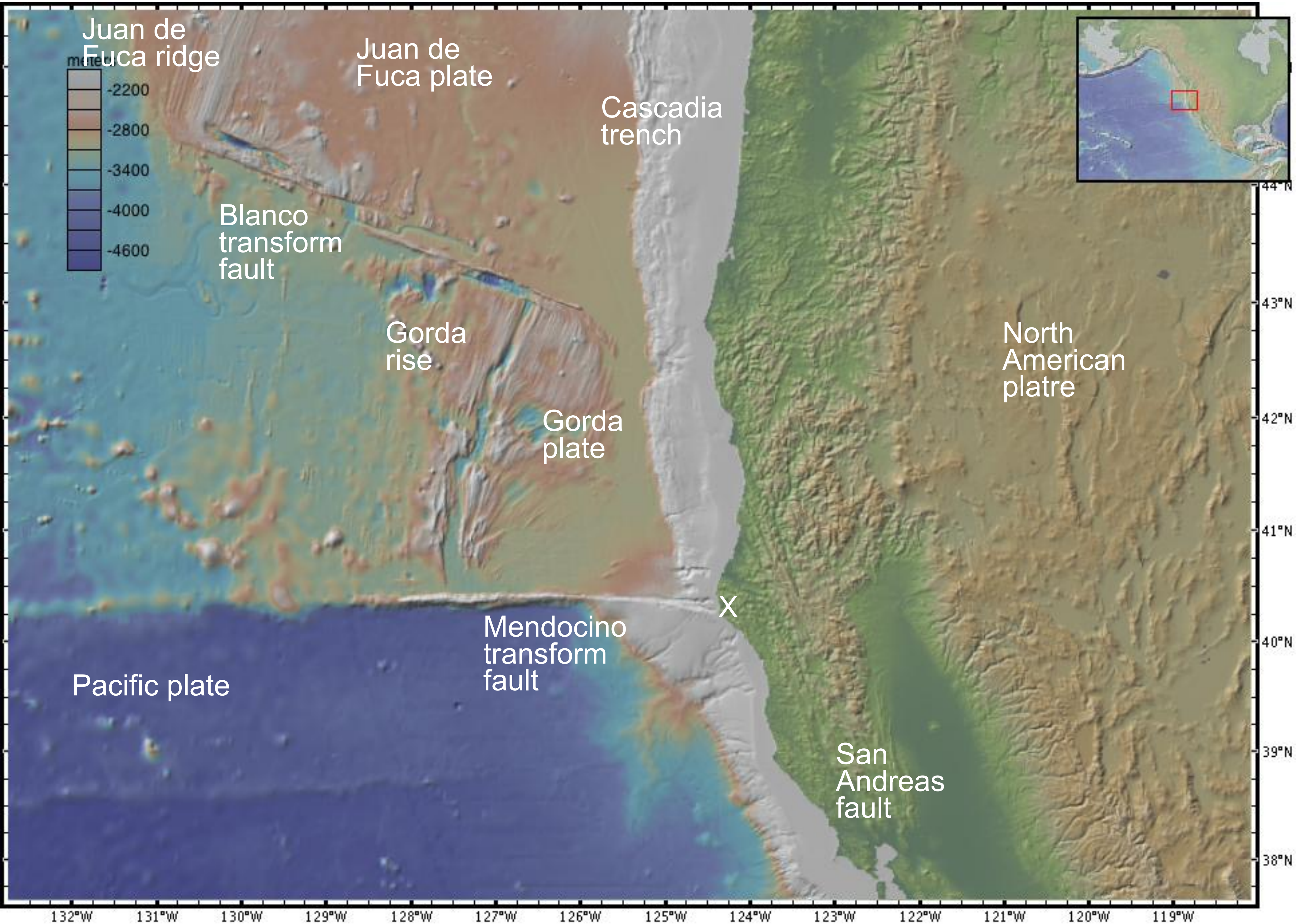




Figure 29. Active faults in the vicinity of the Mendocino triple junction, after Kelsey and Carver (1988). The main strand of the San Andreas fault lies offshore, but major young faulting also occurs inland of the junction. The "Humboldt Plate" (Herd, 1978) may be in the process of being transferred from the North American to the Pacific Plate.

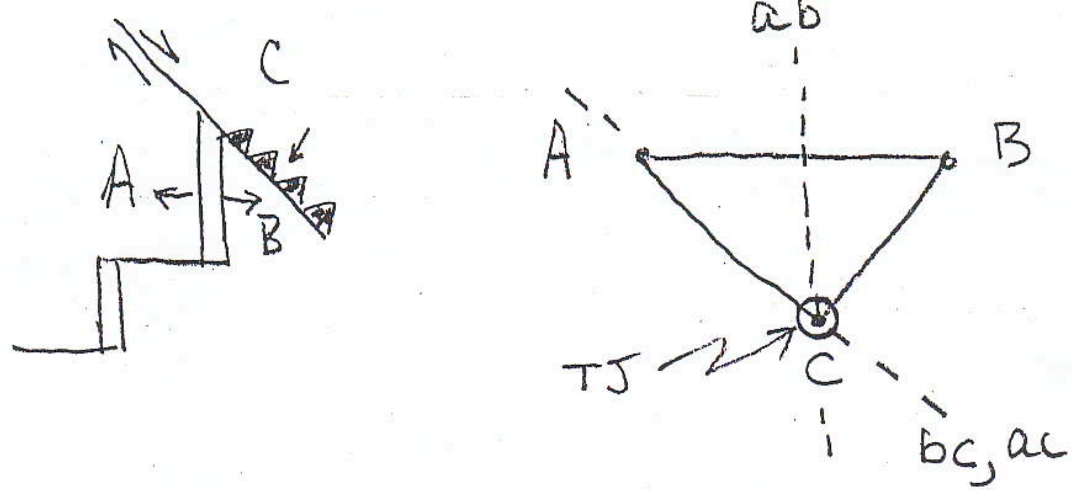
Atwater (1989)


Juan de Fuca ridge
meters
-2200
-2800
-3400
-4000
-4600
Juan de Fuca plate
Cascadia trench
Blanco transform fault
Gorda rise
Gorda plate
North American platre
X
Mendocino transform fault
Pacific plate
San Andreas fault
44°N
43°N
42°N
41°N
40°N
39°N
38°N
132°W
131°W
130°W
129°W
128°W
127°W
126°W
125°W
124°W
123°W
122°W
121°W
120°W
119°W

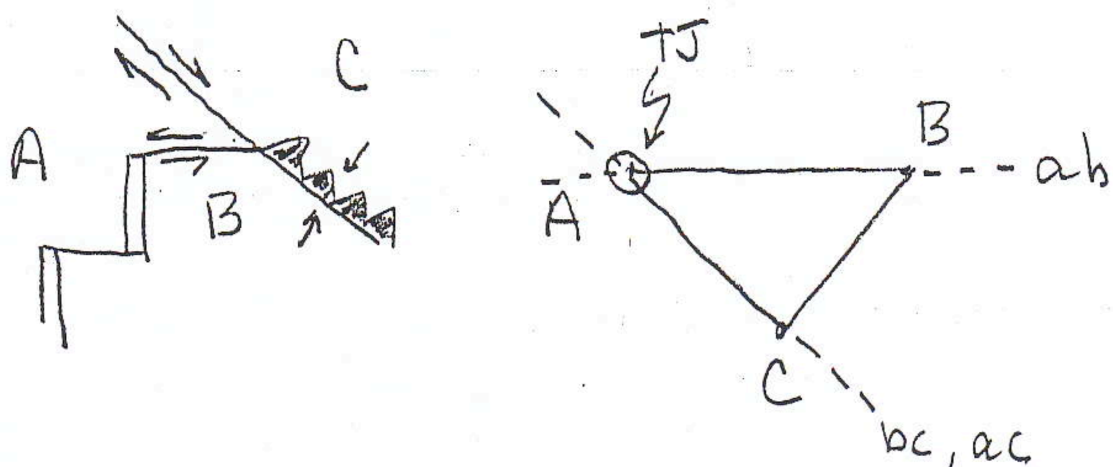
Rivera T.J.:

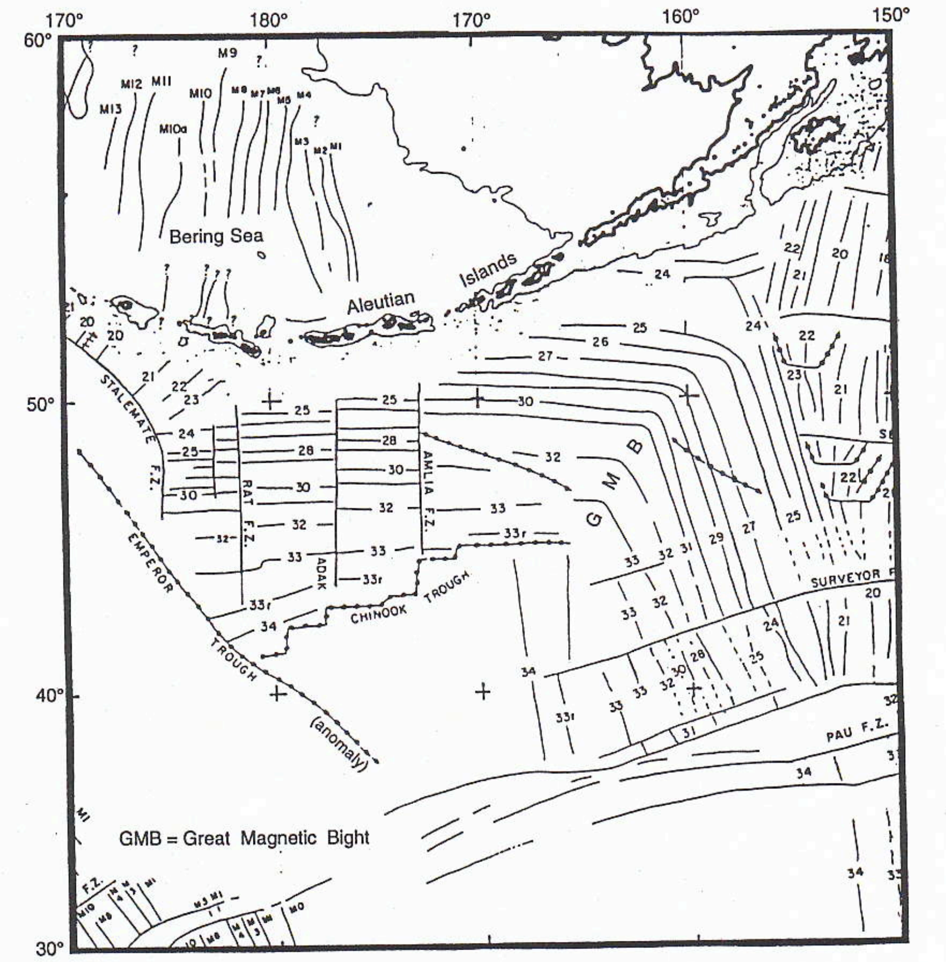
# Flips between TRF and TFF

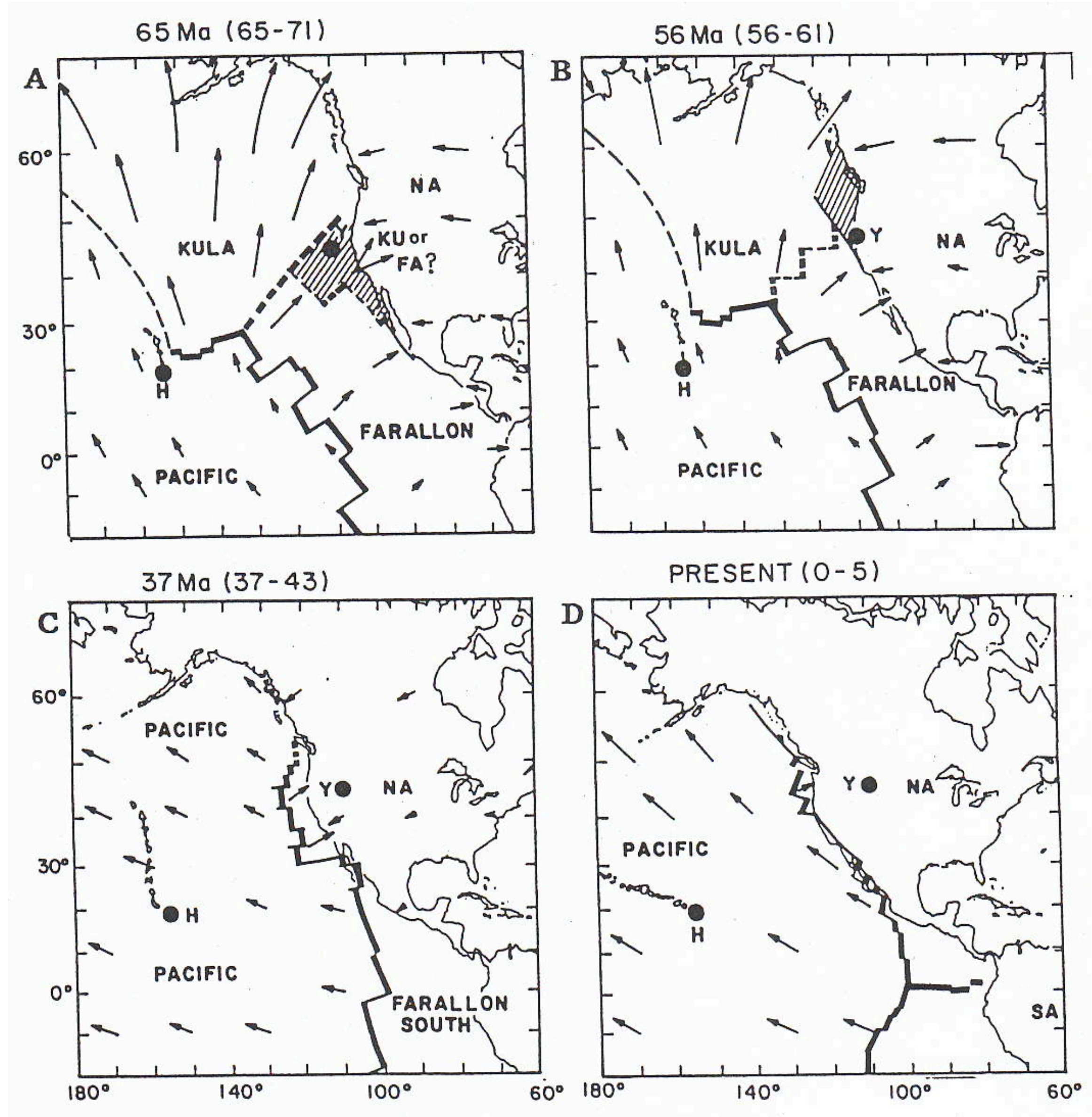
TRF




TFF



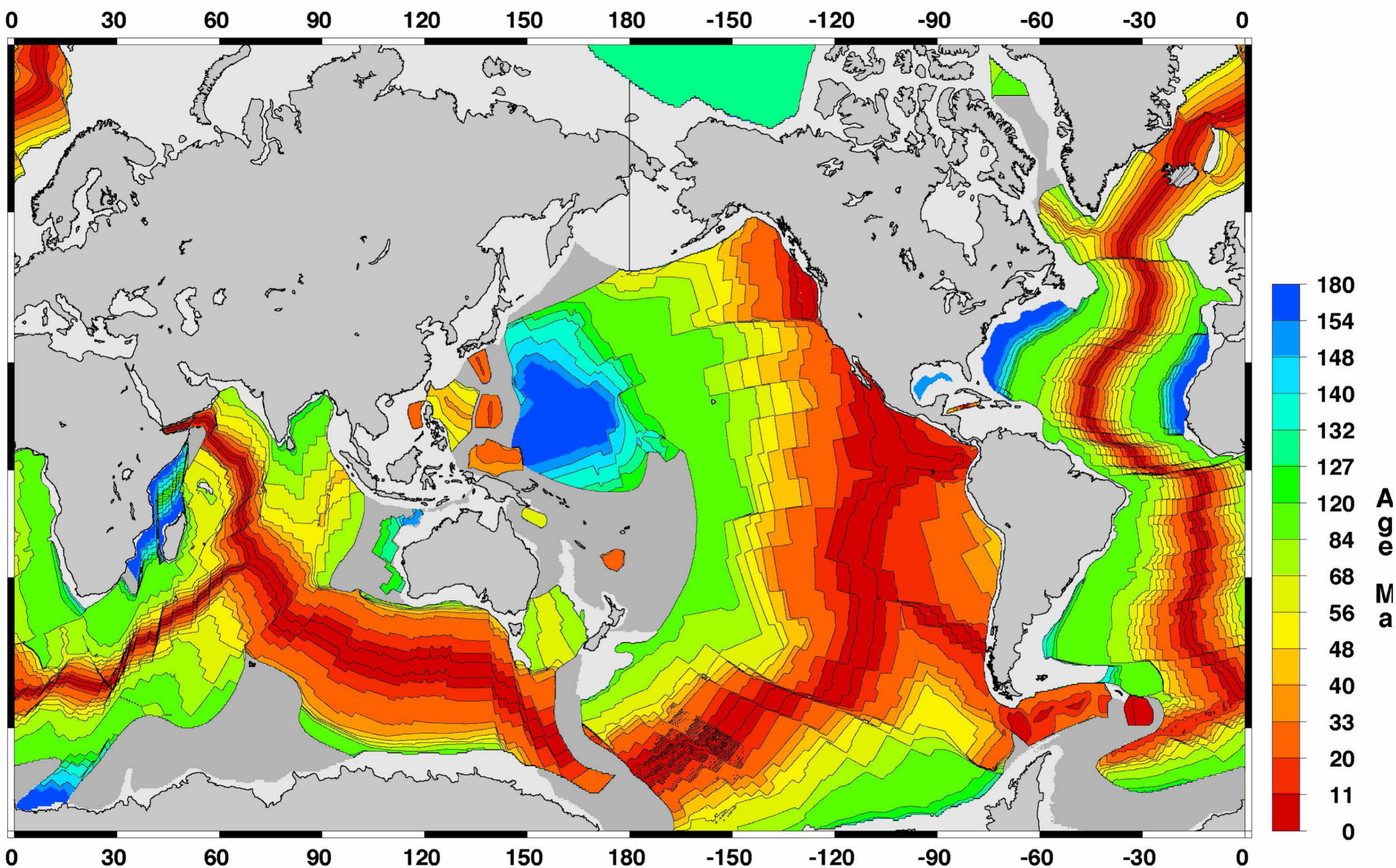


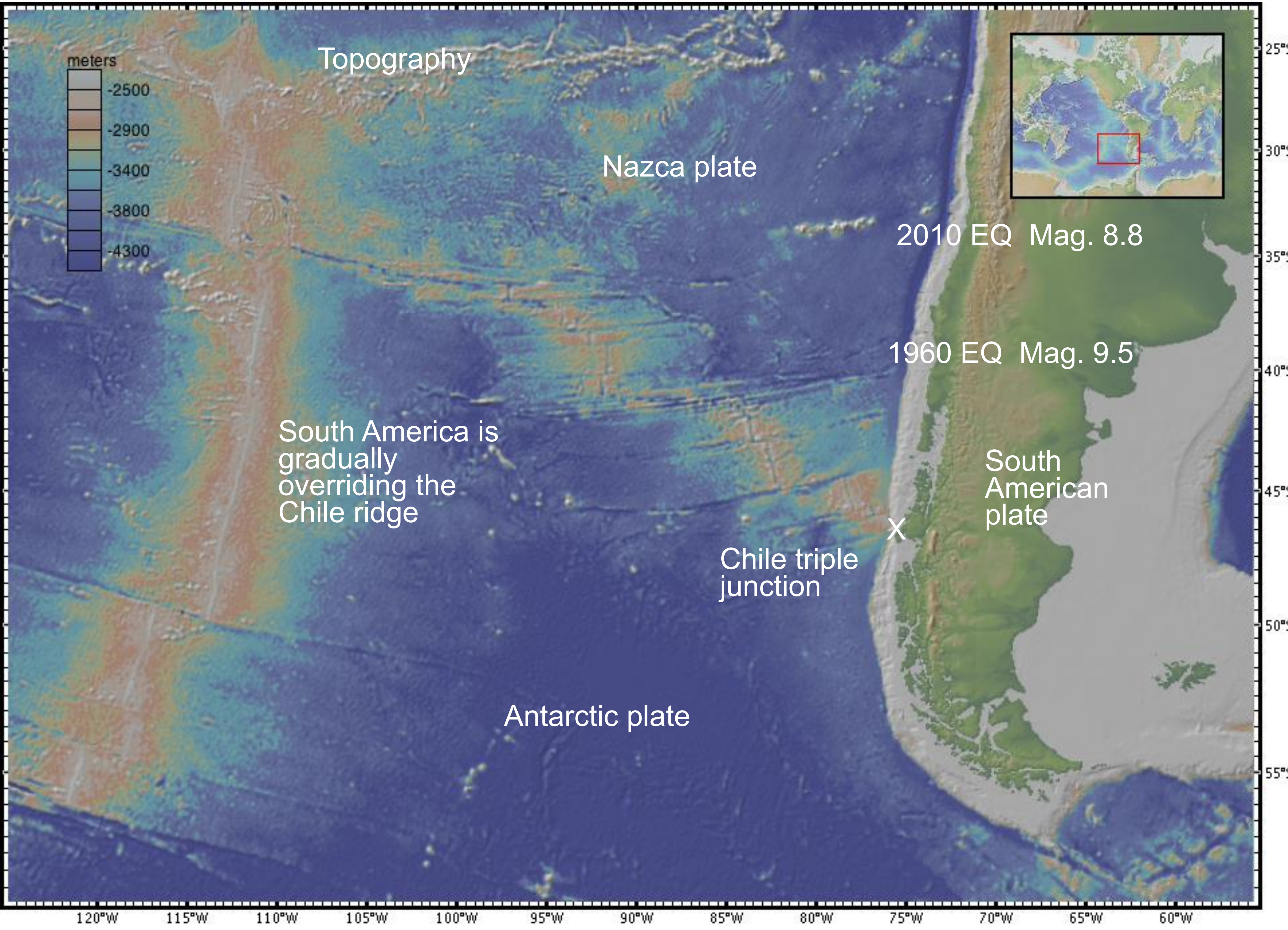

Use spreading rates and directions based on Pac-Far and Pac-Kula magnetic anomalies to determine Kula-Far ridge location

Atwater 1989

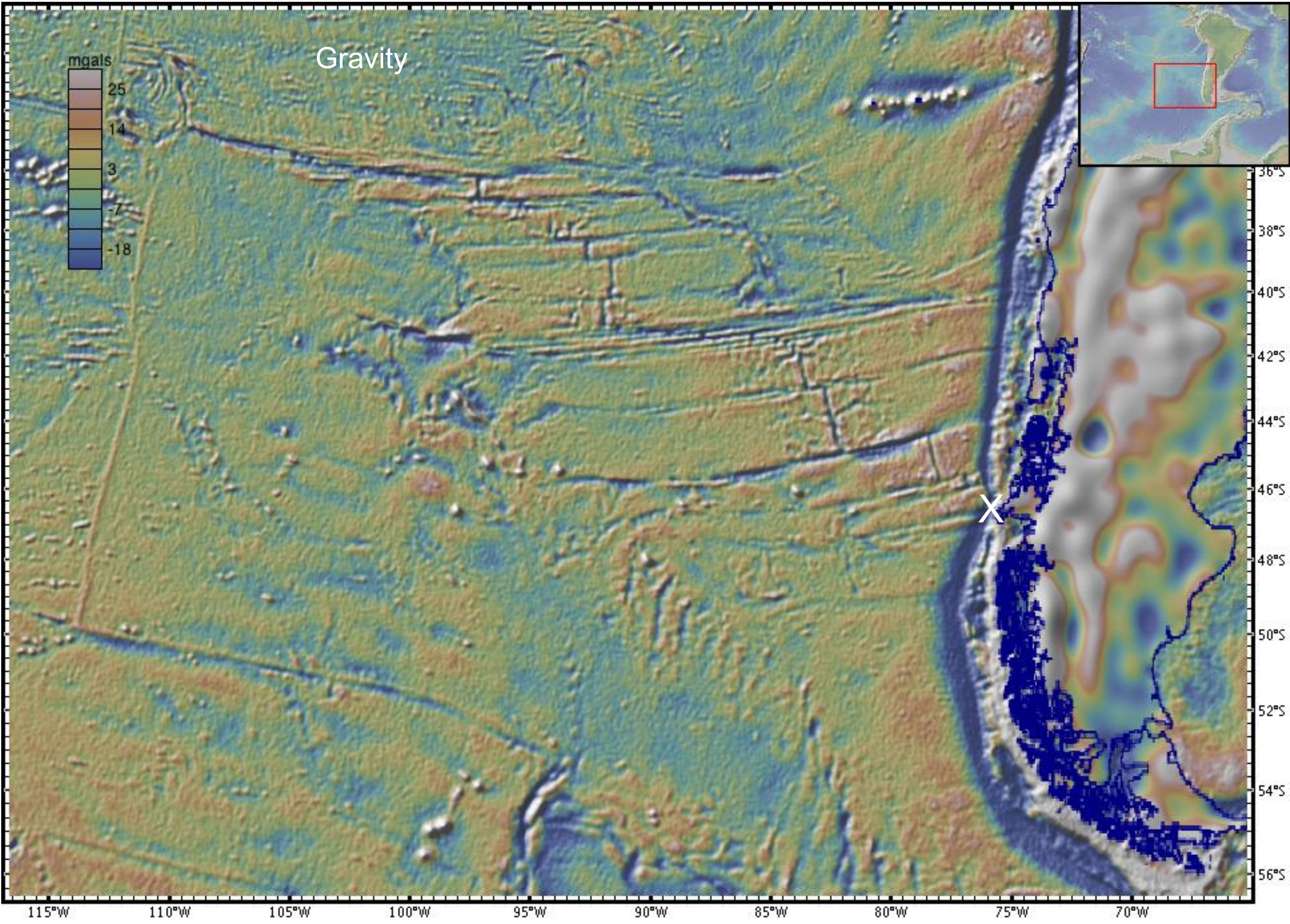
# Digital isochrons of the ocean floor




note: TJ in Southern Chile



Topography
meters
-2500
-2900
-3400
-3800
-4300
Nazca plate
2010 EQ Mag. 8.8
1960 EQ Mag. 9.5
South America is gradually overriding the Chile ridge
South American plate
X
Chile triple junction
Antarctic plate
25°S
30°S
35°S
40°S
45°S
50°S
55°S
120°W
115°W
110°W
105°W
100°W
95°W
90°W
85°W
80°W
75°W
70°W
65°W
60°W


Gravity
mgals
25
14
3
-7
-18
X
36°S
38°S
40°S
42°S
44°S
46°S
48°S
50°S
52°S
54°S
56°S
115°W
110°W
105°W
100°W
95°W
90°W
85°W
80°W
75°W
70°W

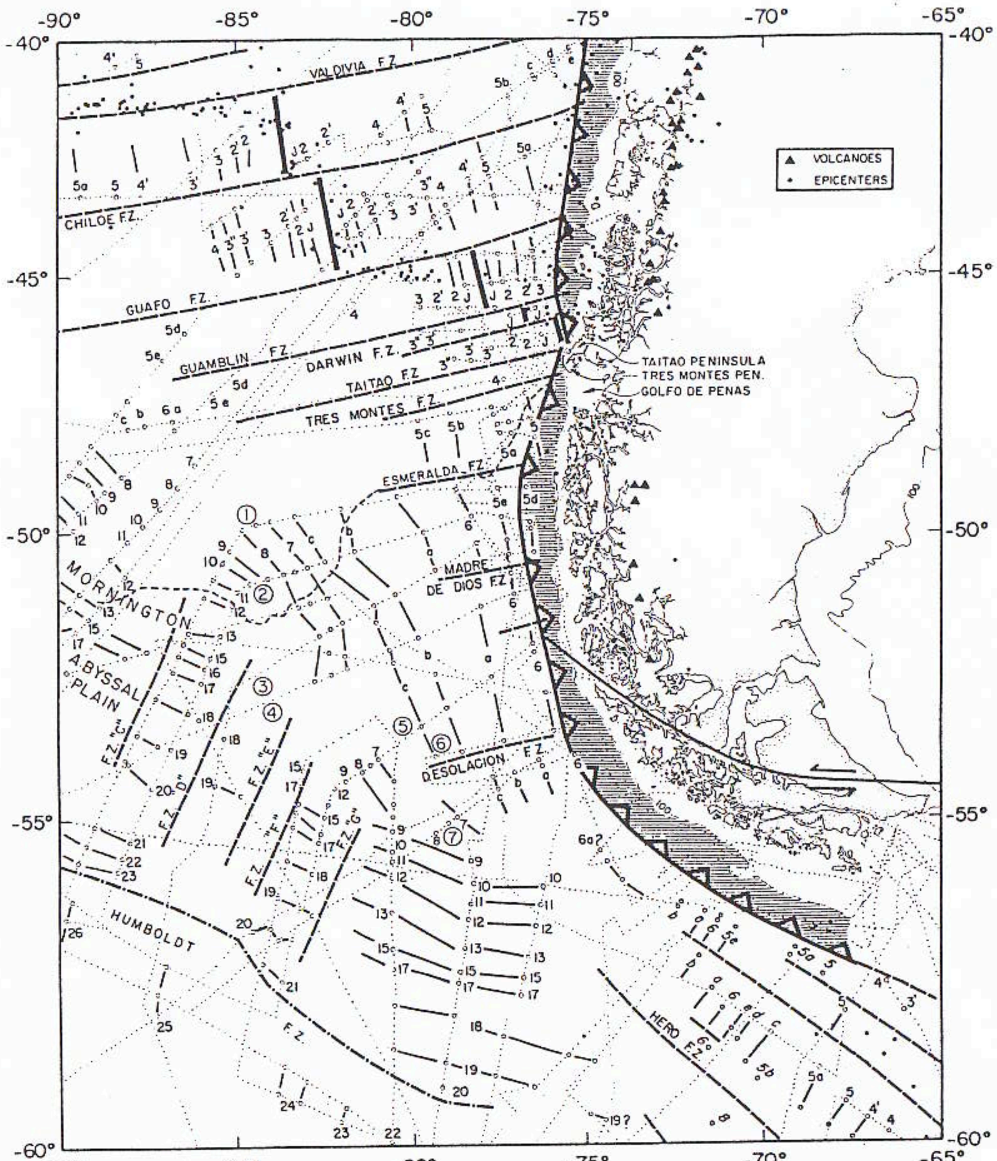


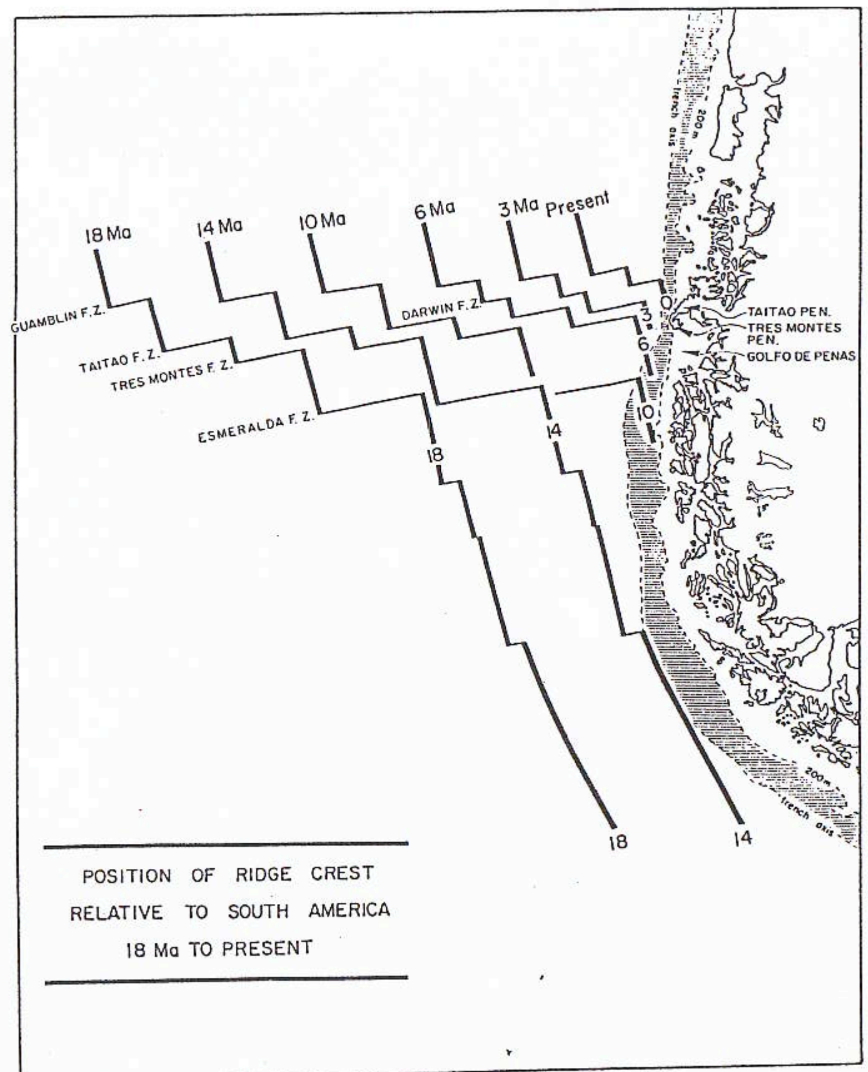

Fig. 2. Revised marine magnetic anomaly map of the southeast Pacific Basin adjacent to southern Chile.

## Ridge Crest Subduction

The Antarctic-Nazca-South America triple junction is migrating northwards along the southern Chile trench, starting near the tip of South America around 15 Ma.

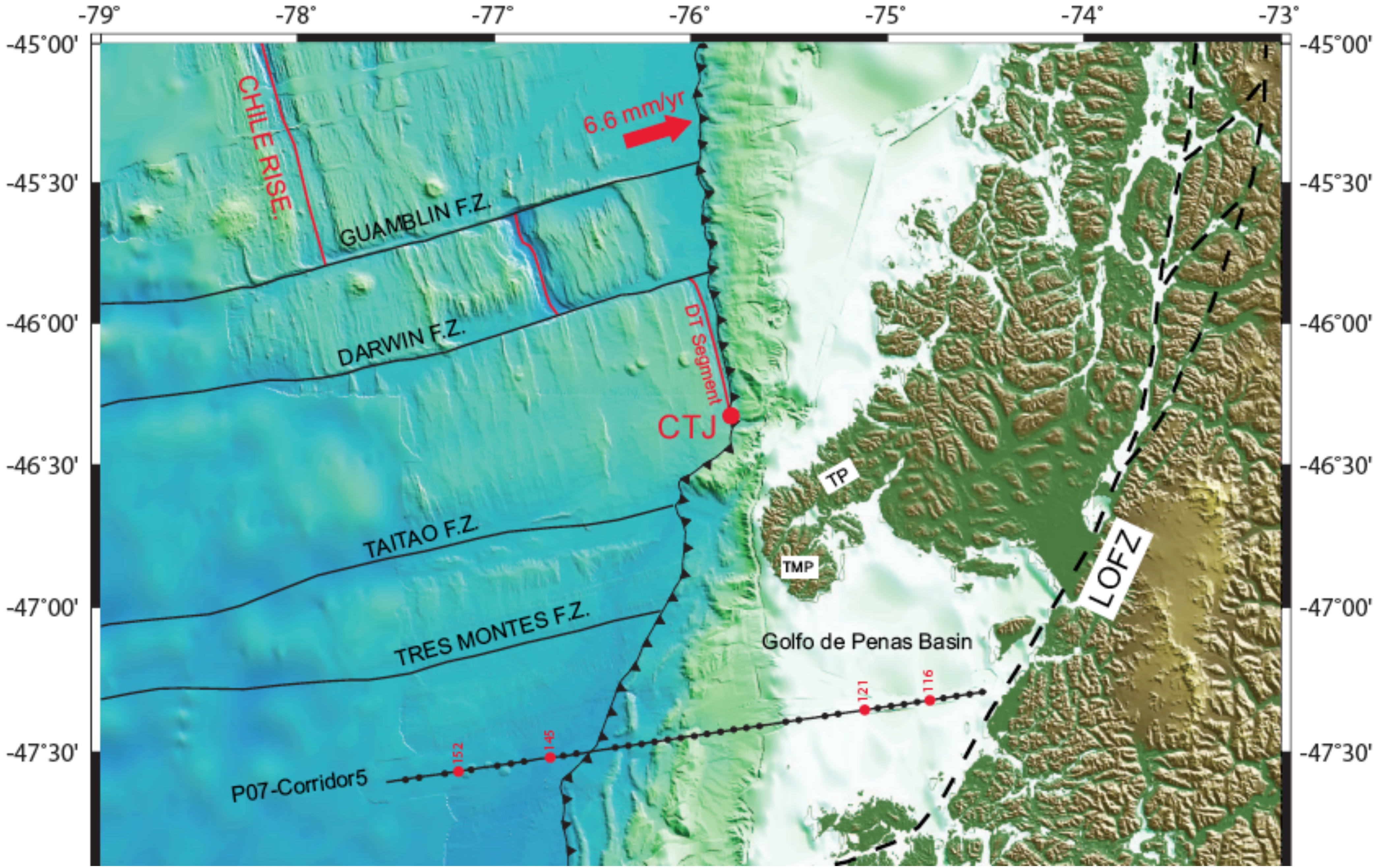
North of the triple junction, the Nazca plate is subducting rapidly (roughly 80 mm/yr), south of the triple junction the Antarctic plate is subducting slowly (roughly 20 mm/yr)

The triple junction alternates between TTR and TTF.



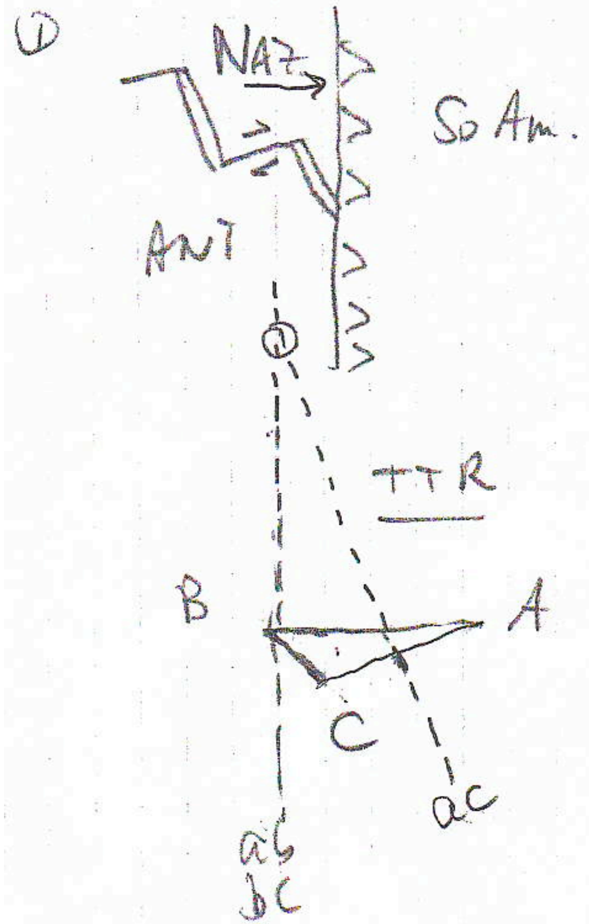

Study what happens before during and after a ridge-trench collision

Compare Pac-Far-NoAm

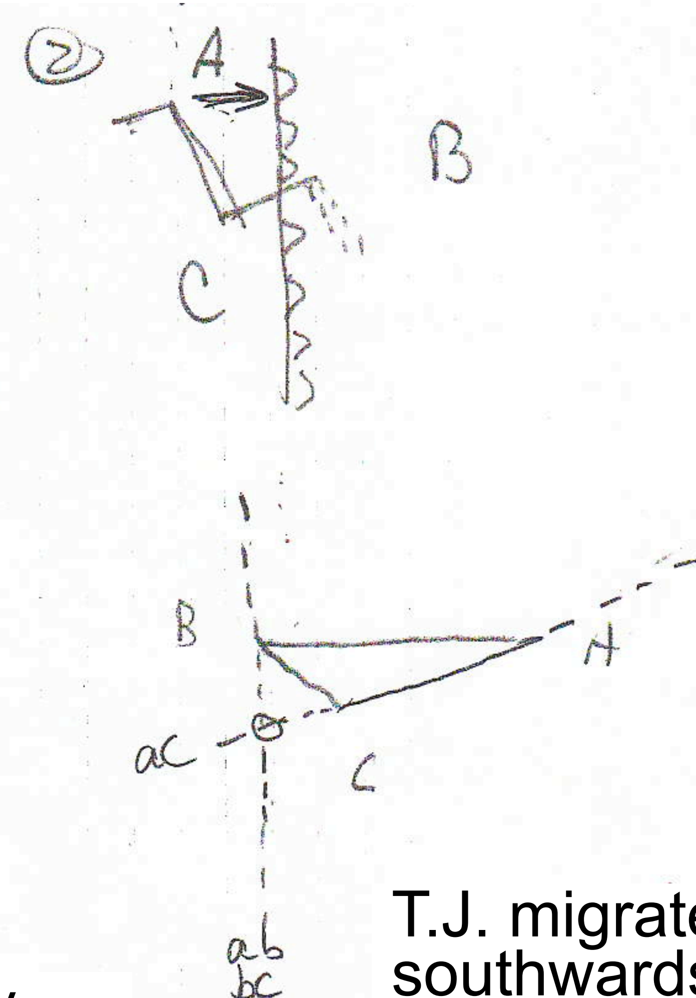


-79°
-78°
-77°
-76°
-75°
-74°
-73°
-45°00'
-45°30'
-46°00'
-46°30'
-47°00'
-47°30'
CHILE RISE
6.6 mm/yr
GUAMBLIN F.Z.
DARWIN F.Z.
DT Segment
CTJ
TP
TMP
TAITAO F.Z.
TRES MONTES F.Z.
LOFZ
Golfo de Penas Basin
116
121
145
152
P07-Corridor5

South Chile 2 configurations

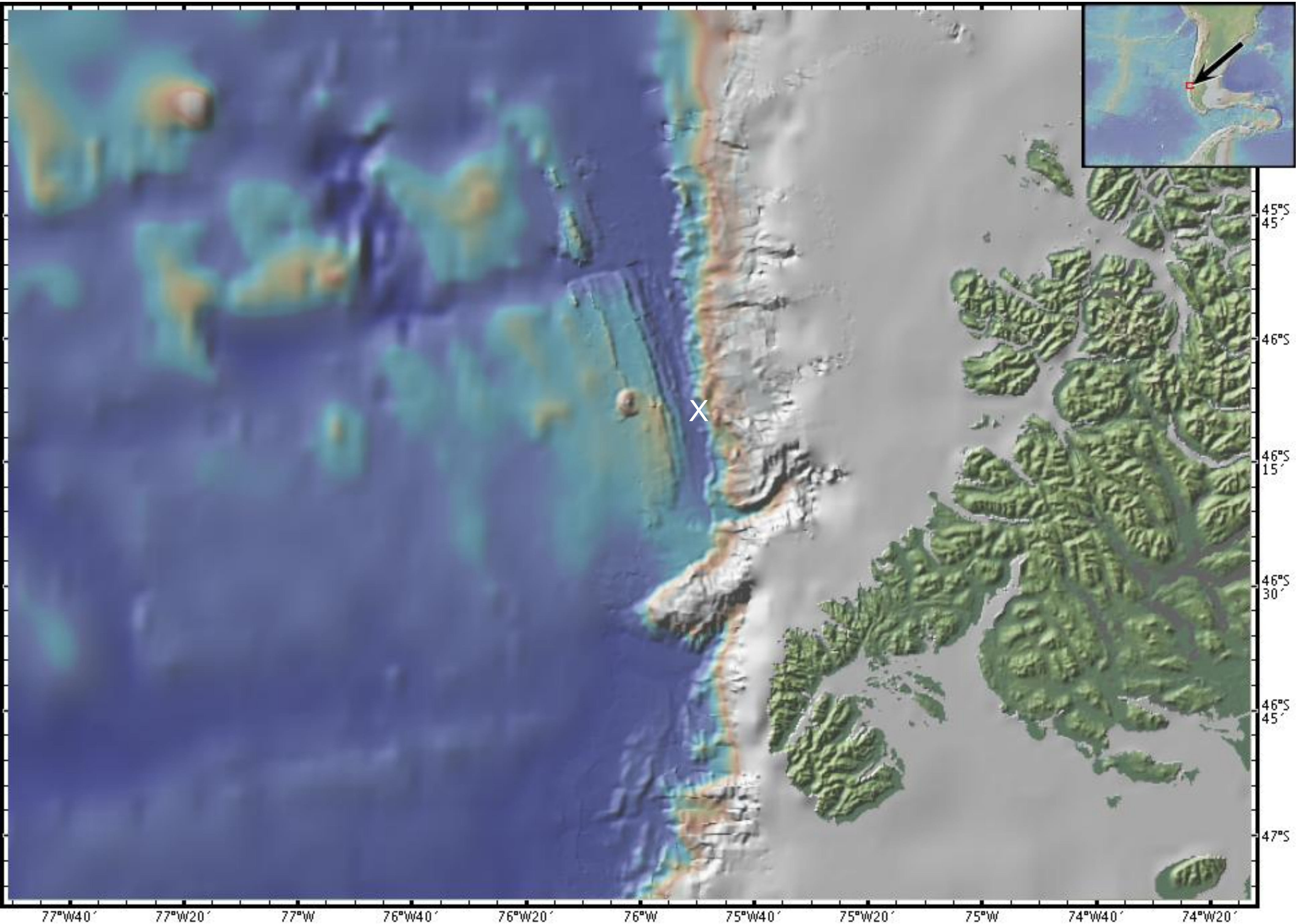


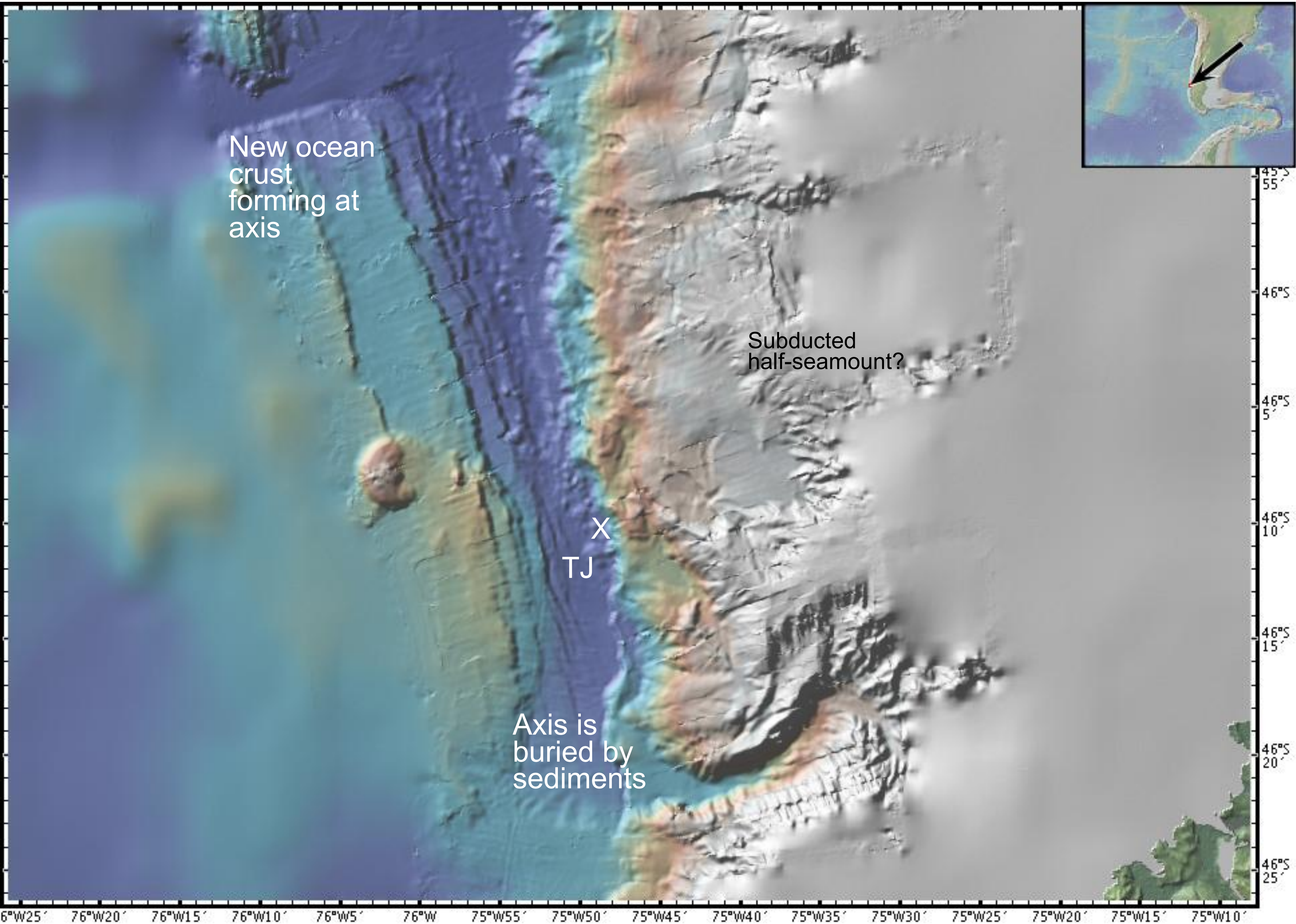

T.J. migrates <u>rapidly</u> northwards



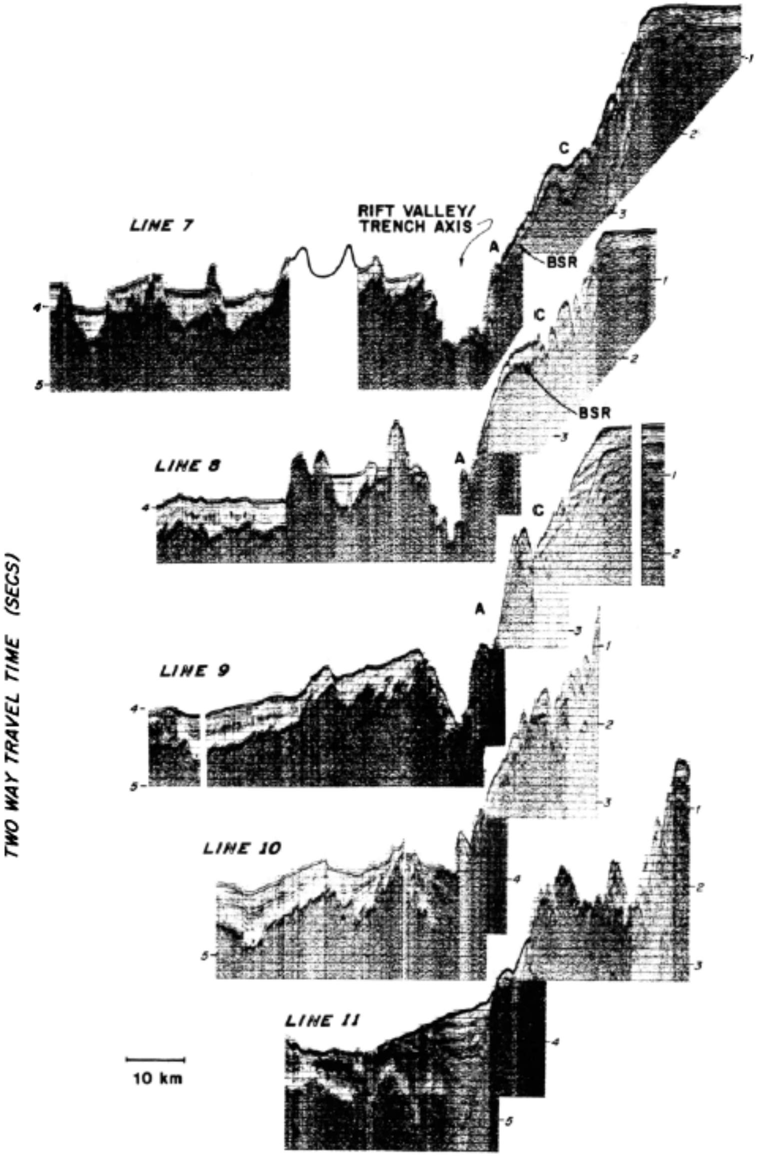

T.J. migrates <u>slowly</u> southwards

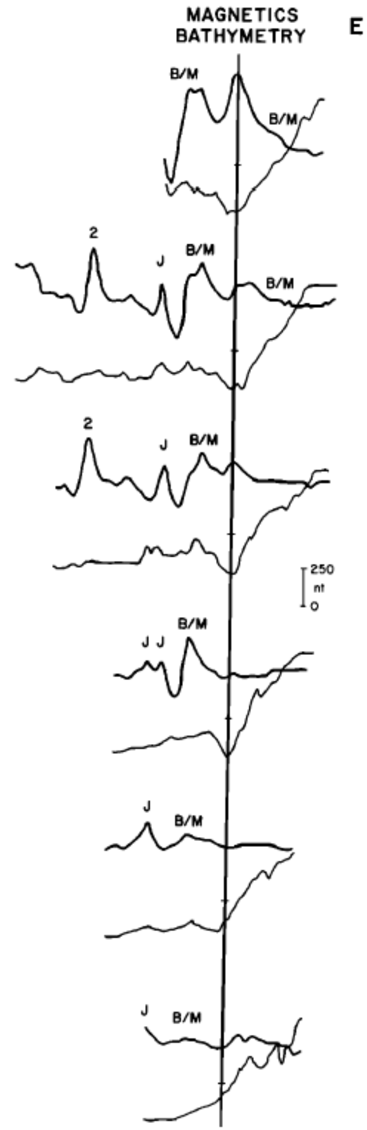
<u>both</u> configurations are <u>stable</u>


X
45°S 45´
46°S
46°S 15´
46°S 30´
46°S 45´
47°S
77°W40´
77°W20´
77°W
76°W40´
76°W20´
76°W
75°W40´
75°W20´
75°W
74°W40´
74°W20´

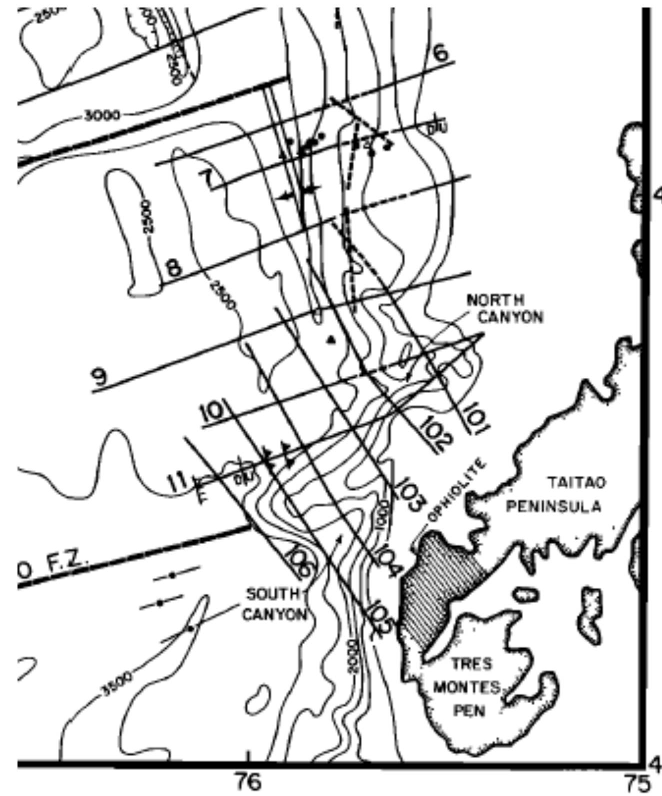

New ocean crust forming at axis
Subducted half-seamount?
X
TJ
Axis is buried by sediments
45°S 55´
46°S
46°S 5´
46°S 10´
46°S 15´
46°S 20´
46°S 25´
76°W25´
76°W20´
76°W15´
76°W10´
76°W5´
76°W
75°W55´
75°W50´
75°W45´
75°W40´
75°W35´
75°W30´
75°W25´
75°W20´
75°W15´
75°W10´

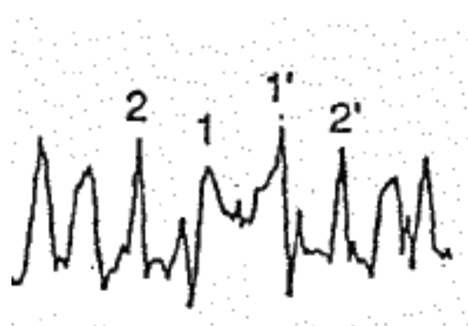
# Ridge subduction: Spreading at the Chile triple junction



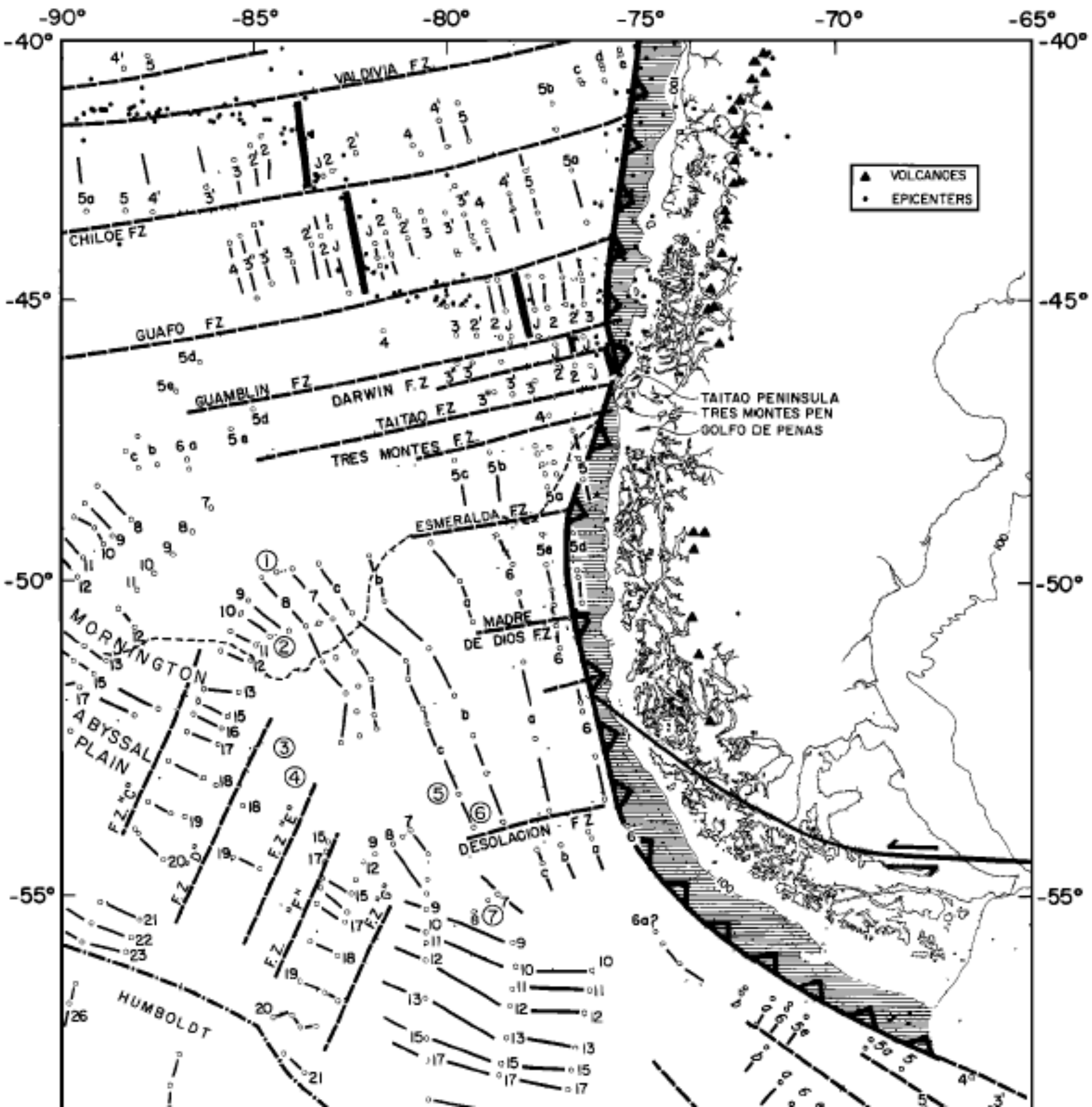

The shape of the Central anomaly indicates when layer 2A stops being formed;
Between line 8 and 9 the axial magnetic high dissapears

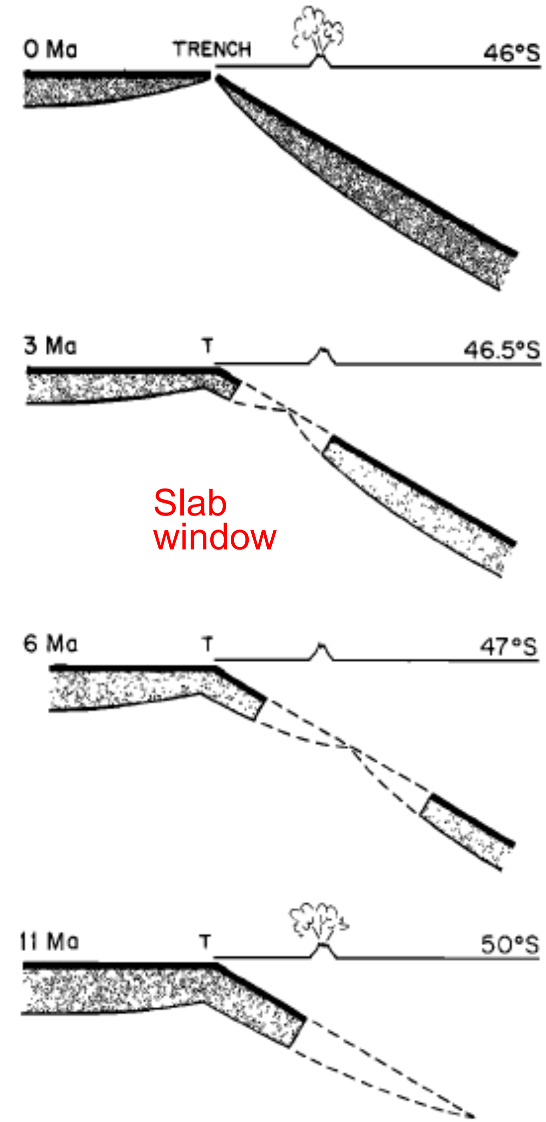



Compare Pac-Ant ridge profile: Note the small "axial high" right over the axis; due to really fresh basalts

There is a gap in volcanism south of the triple junction corresponding to the segments where the crust passing beneath the volcanic line (~125 km depth) didn't form at a spreading center;



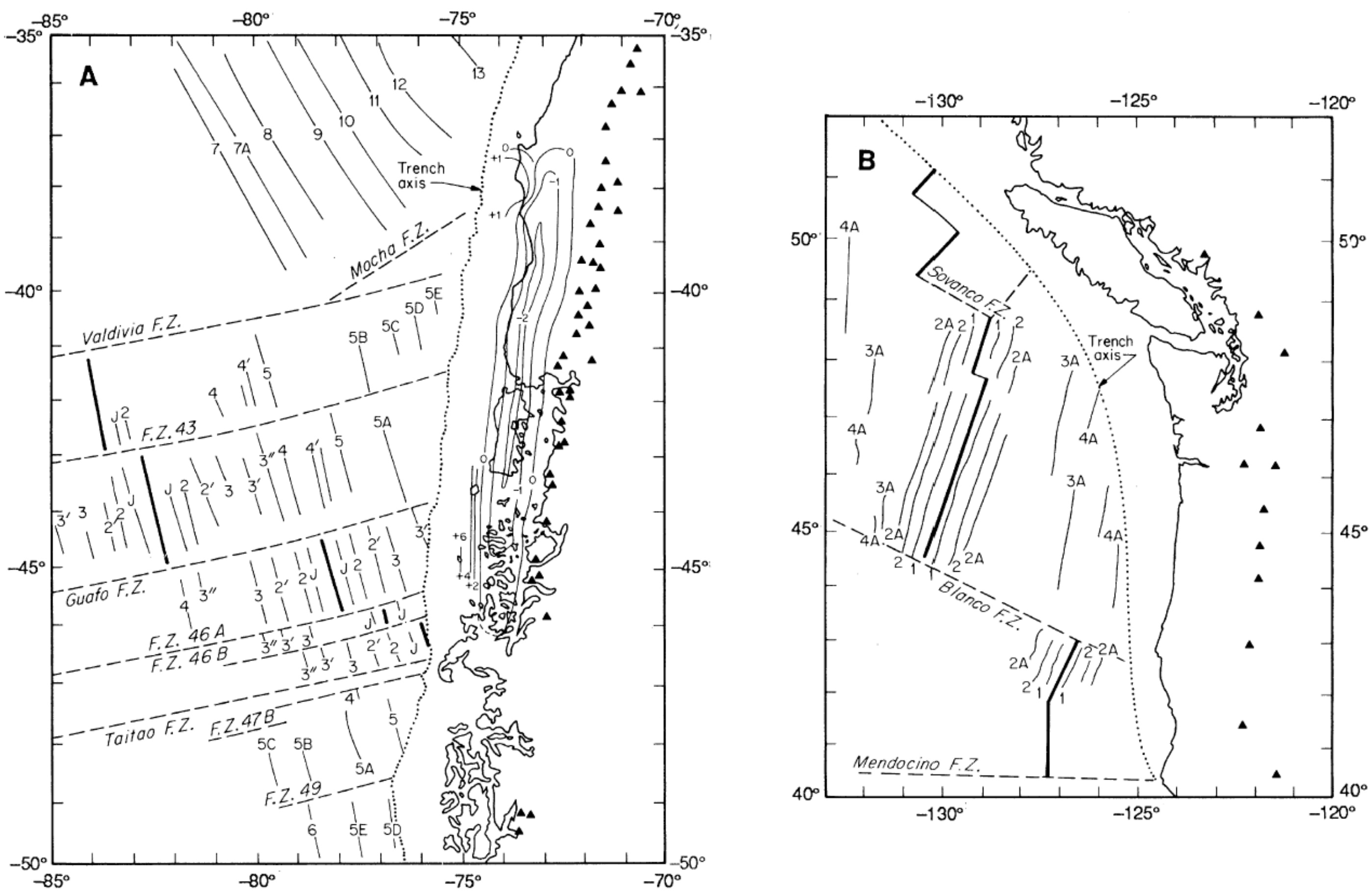




This indicates that water squeezed from subducted oceanic crust is important in generating magmas

# Earthquake Hazards on the Cascadia Subduction Zone

Thomas H. Heaton and Stephen H. Hartzell (1987)

Large subduction earthquakes on the Cascadia subduction zone pose a potential seismic hazard. Very young oceanic lithosphere (10 million years old) is being subducted beneath North America at a rate of approximately 4 centimeters per year. The Cascadia subduction zone shares many characteristics with subduction zones in southern Chile, southwestern Japan, and Colombia,




Similarities between Southern Chile trench and Cascadia:

Is subduction of young crust a predictor of large earthquakes?

(But, 120 Ma crust involved in Japan 2011)

THE NEW YORKER


ANNALS OF SEISMOLOGY JULY 20, 2015 ISSUE

# THE REALLY BIG ONE

*An earthquake will destroy a sizable portion of the coastal Northwest. The question is when.*