APPLYING GEODESY TO GEOSCIENCE 1

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Jet Propulsion Laboratory
California Institute of Technology

PART 1 Data Uncertainties

PART 2 Rigid Plates

PART 3 Plate Motion From Geodesy

PART 4 Plate Motion From Geology

PART 5 Postglacial Rebound

PART 6 Earth Center Motion

PART 7 Spin Axis Wander

Earthquake Research Institute 27 August 2002

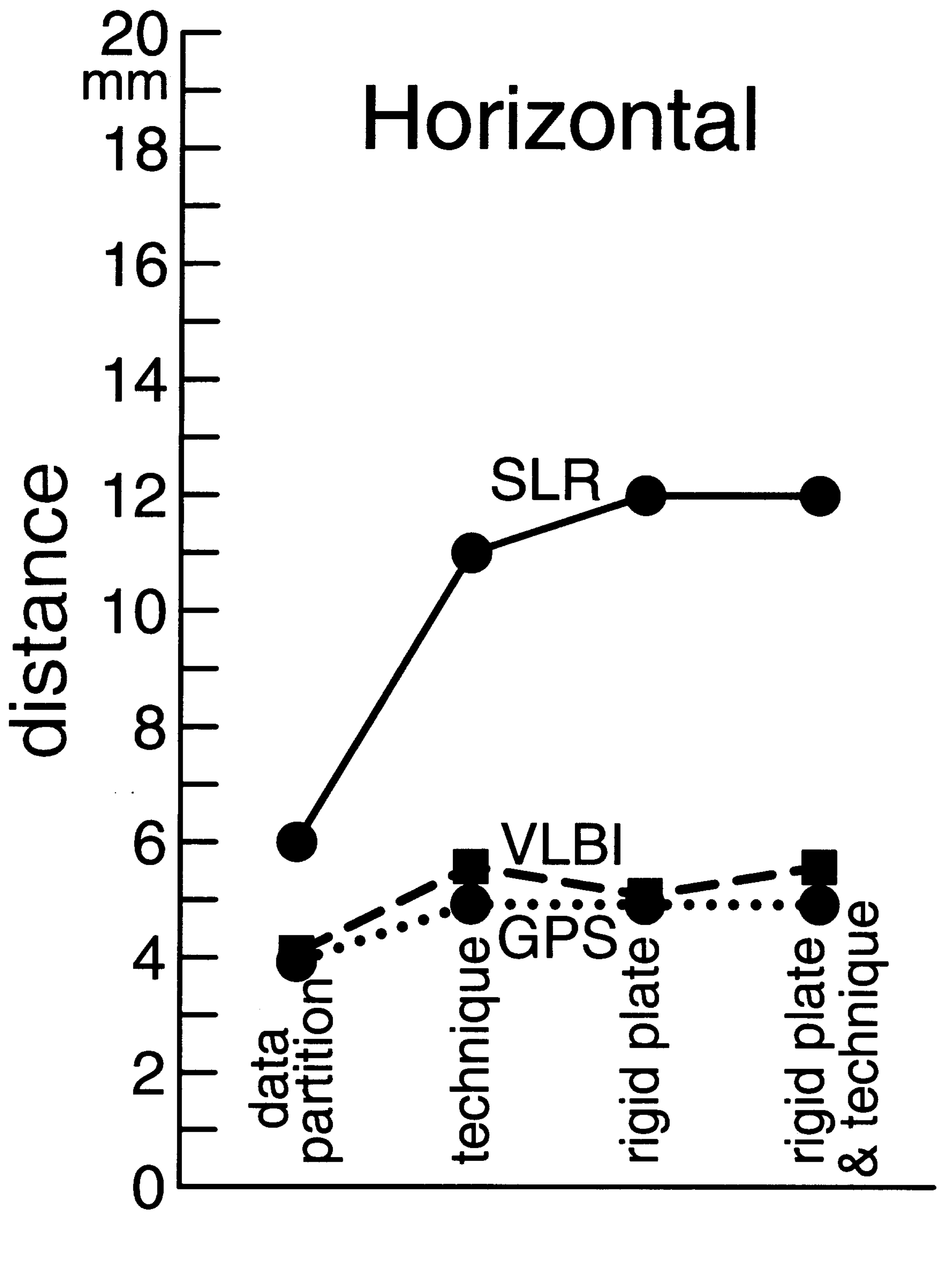
PART 1
Data Uncertainties

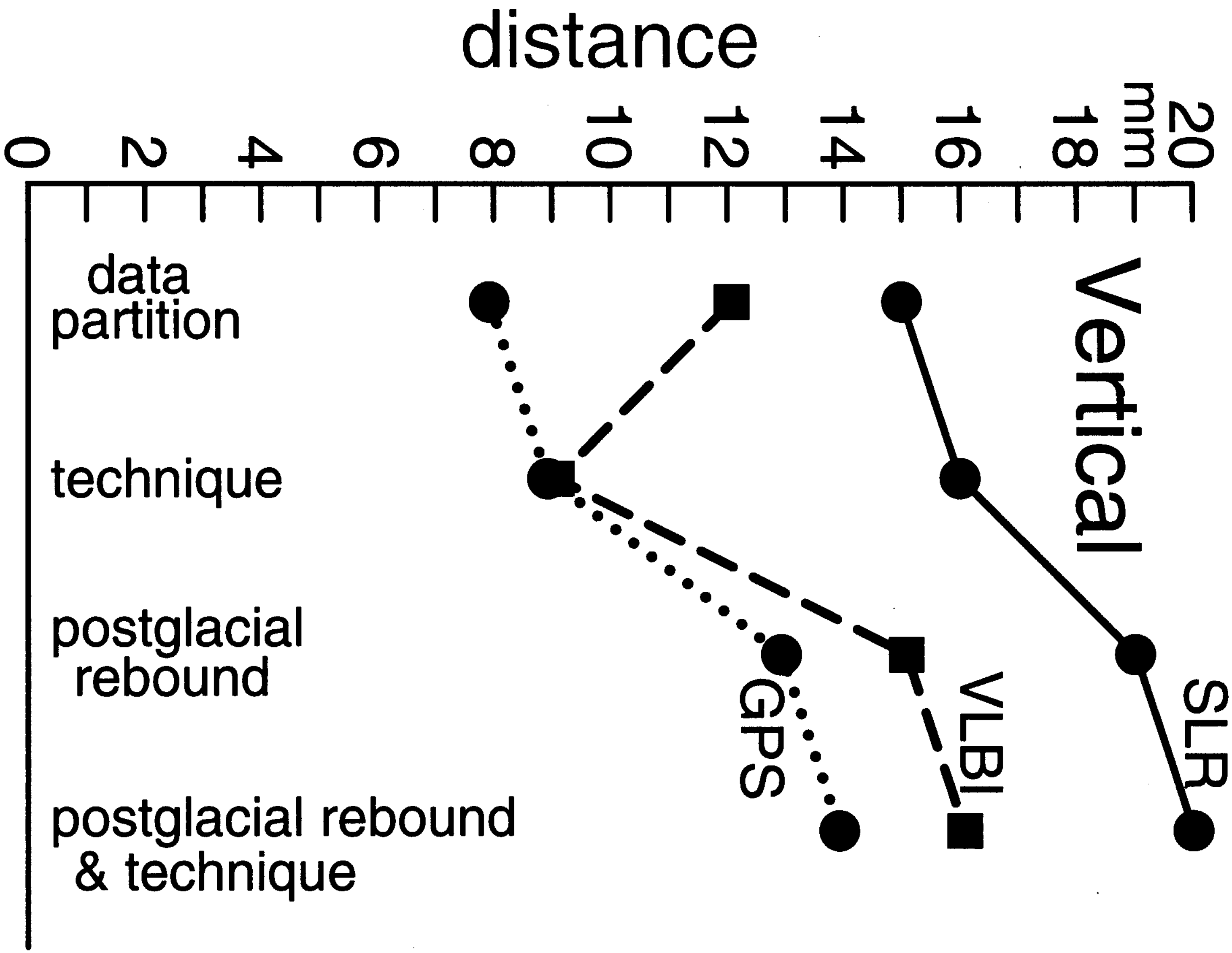
Error Budget

$$\left(\text{true error}\right)^2 = \left(\text{random error}\right)^2 + \left(\text{system error}\right)^2$$

random error = dispersion of position estimates about constant velocity

$$\text{system error} = \frac{\text{distance}}{\text{time}}$$


Horizontal
distance
mm
0
2
4
6
8
10
12
14
16
18
20
SLR
VLBI
GPS
data partition
technique
rigid plate
rigid plate & technique


distance
Vertical
mm
0
2
4
6
8
10
12
14
16
18
20
data partition
technique
postglacial rebound
postglacial rebound & technique
SLR
VLBI
GPS

ERROR BUDGET

$$\left(\text{true error}\right)^2 = \left(\text{random error}\right)^2 + \left(\text{system error}\right)^2$$

$$\text{random error} = \text{dispersion of position estimates about constant velocity}$$

$$\text{system error} = \frac{\text{distance}}{\text{time}}$$

SCIENCE APPLICATIONS

① How big are the true GPS velocity errors?

horizontal= 4 mm/time
vertical= 8 mm/time

How do we know?

data partitioning
technique comparison
rigid plates

Conclusion

GPS velocities are extremely accurate.

PART 2
Rigid Plates

GEODVEL

DATA

site velocities

30	VLBI	1979–1999	Ma Ryan
20	SLR	1976–2000	Eanes
104	GPS	1991–2001	Heflin
154			

PARAMETERS

angular velocities

North America	Nubia
Eurasia	Antarctica
Pacific	Nazca
Australia	Somalia
South America	

horizontal velocities

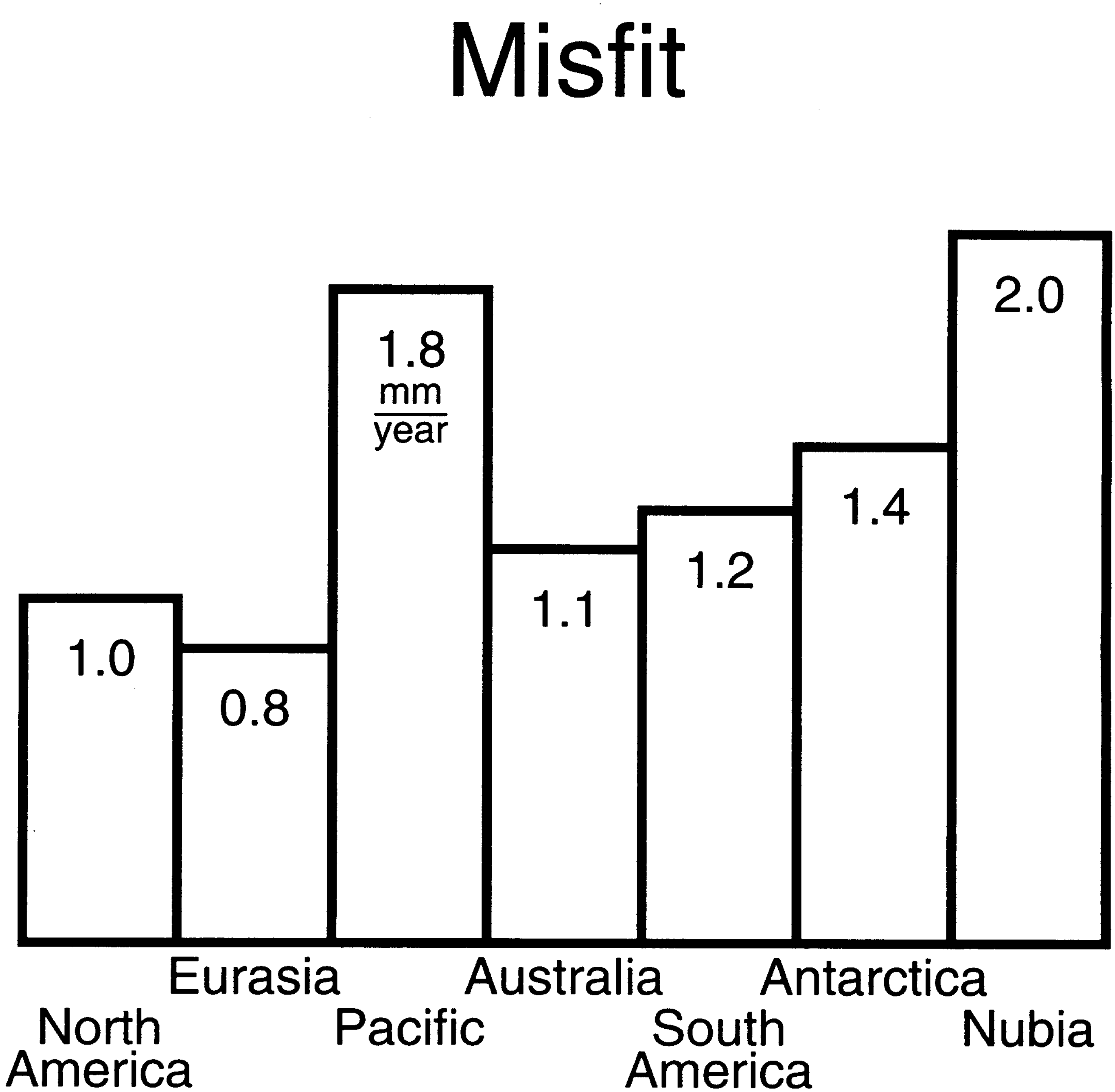
Bahrain (Arabia)
Bangalore (India)

translational velocities

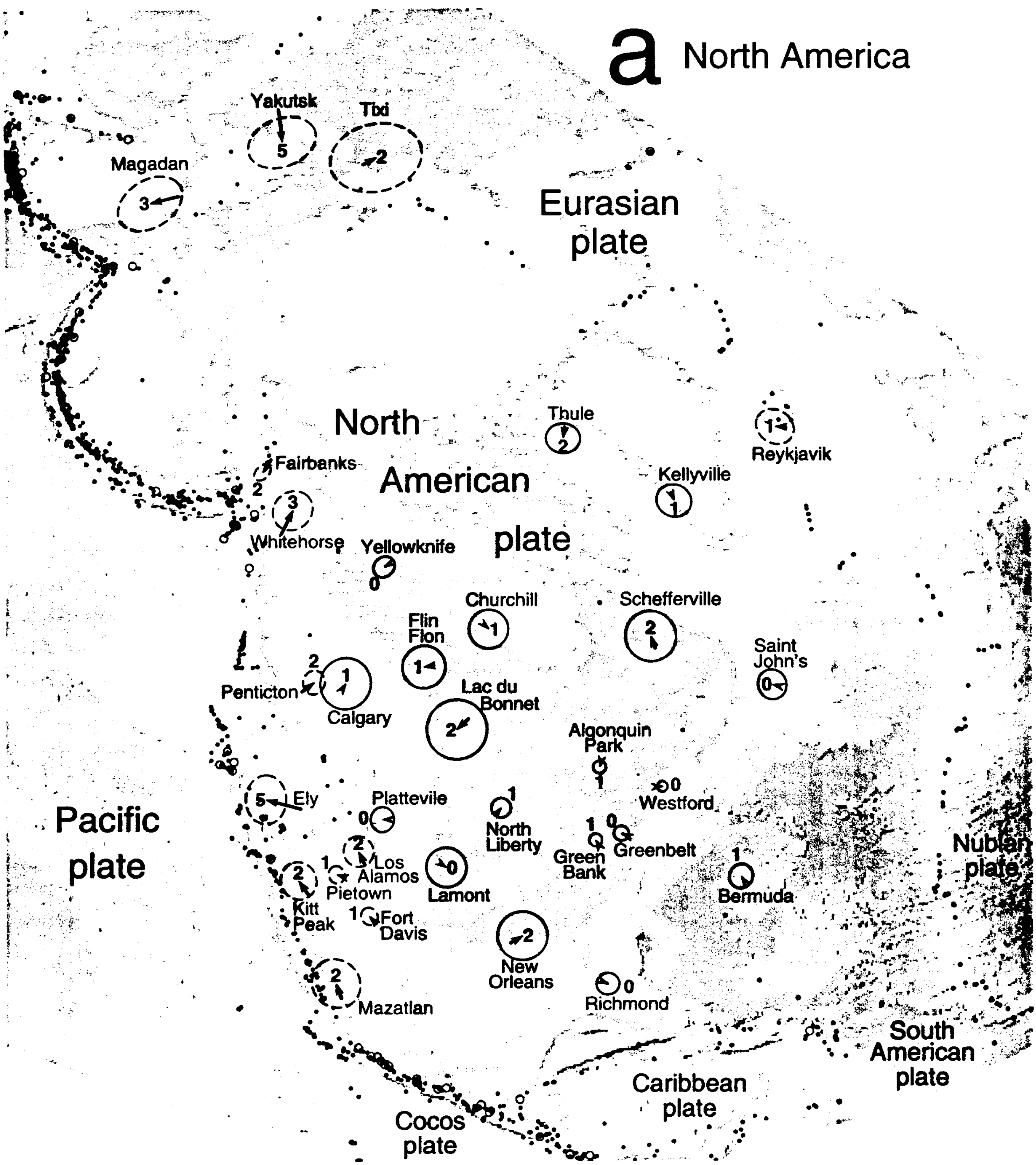
VLBI GPS

rotational velocities

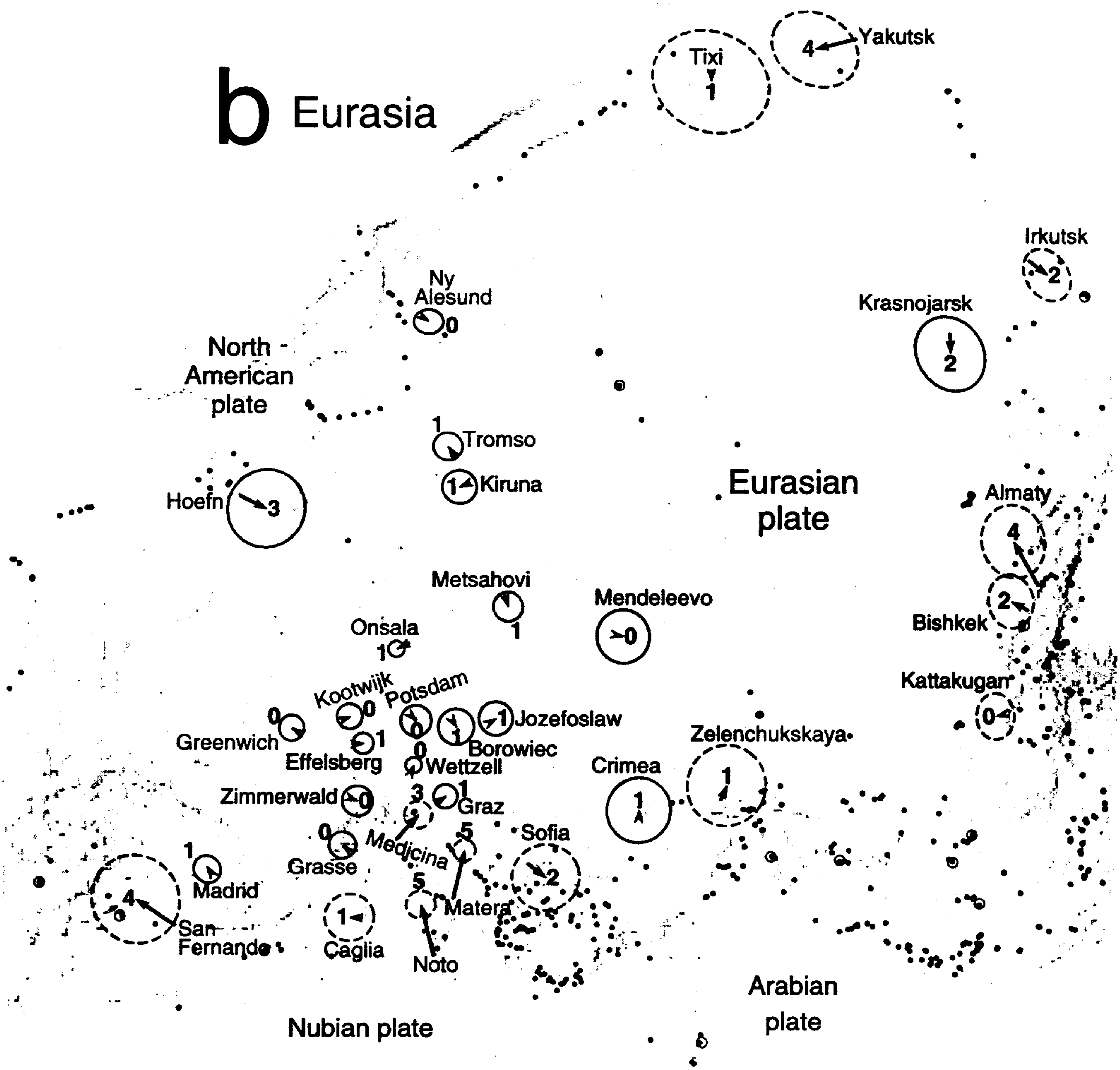
VLBI SLR GPS



Misfit
1.0
0.8
1.8
mm
year
1.1
1.2
1.4
2.0
North America
Eurasia
Pacific
Australia
South America
Antarctica
Nubia

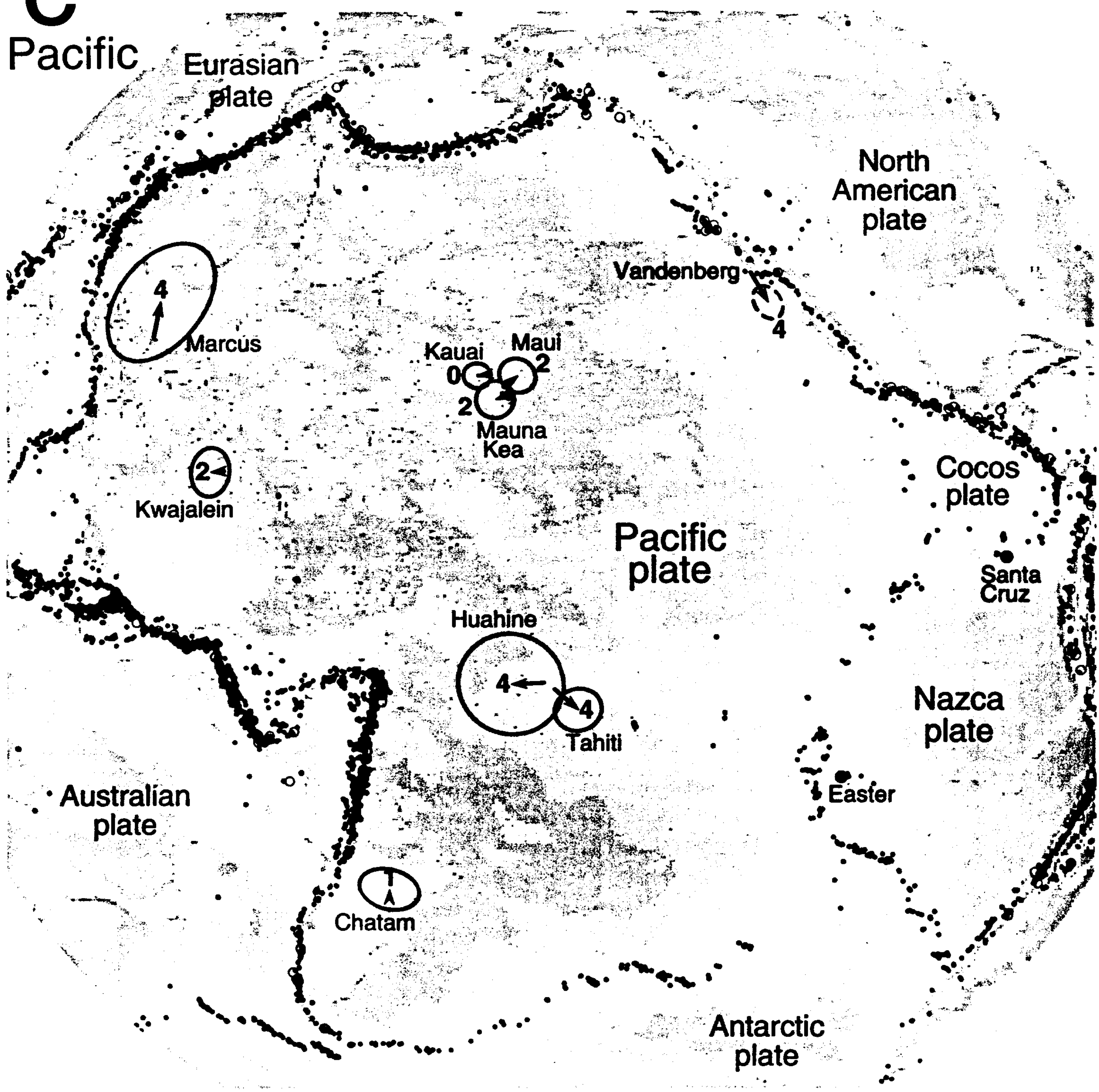


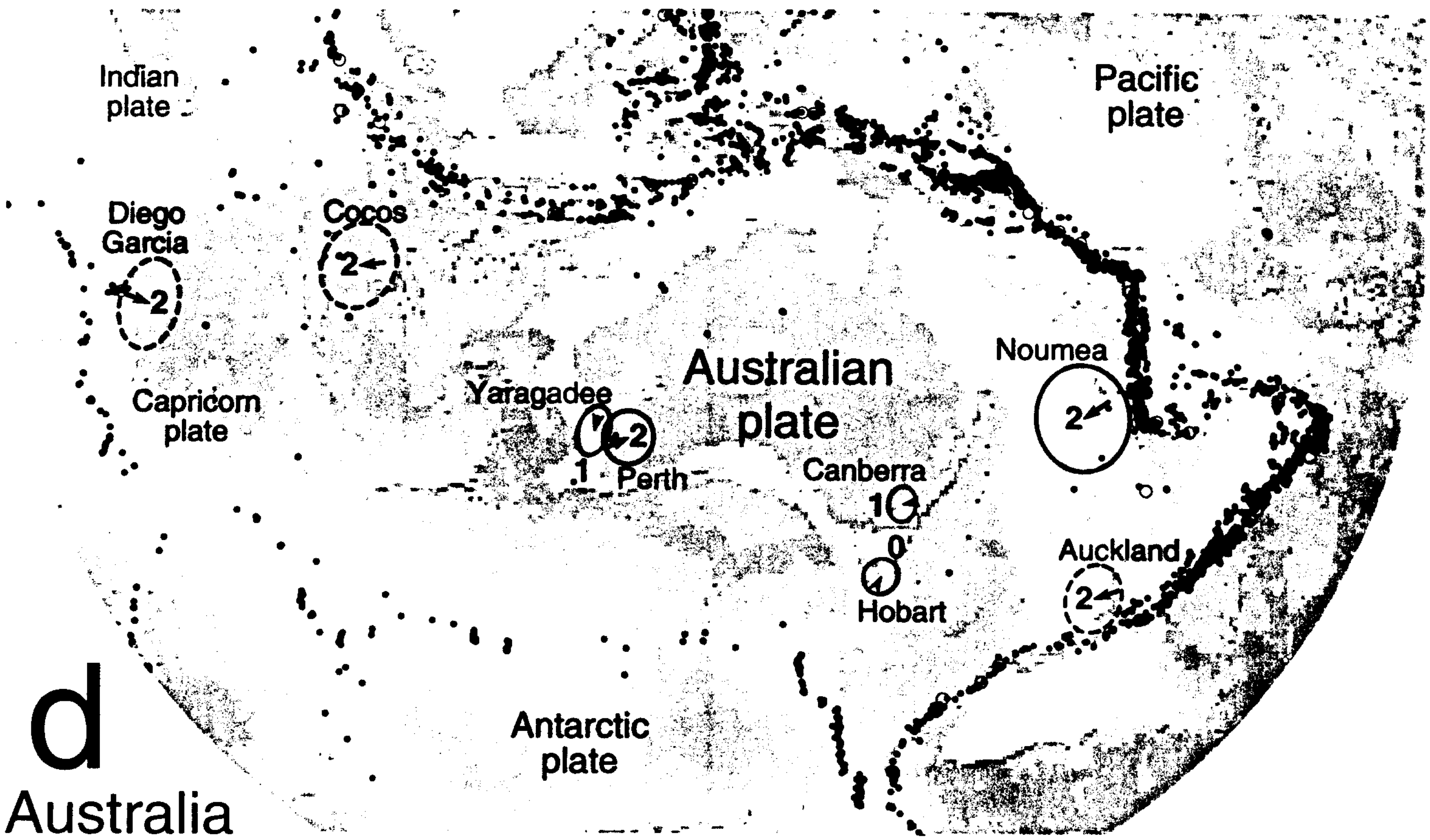
a
North America
Yakutsk
Tixi
Magadan
Eurasian plate
North American plate
Thule
Reykjavik
Fairbanks
Kellyville
Whitehorse
Yellowknife
Churchill
Schefferville
Flin Flon
Saint John's
Penticton
Calgary
Lac du Bonnet
Algonquin Park
Westford
Ely
Platteville
North Liberty
Green Bank
Greenbelt
Pacific plate
Los Alamos
Pietown
Lamont
Bermuda
Nubian plate
Kitt Peak
Fort Davis
New Orleans
Mazatlan
Richmond
South American plate
Caribbean plate
Cocos plate



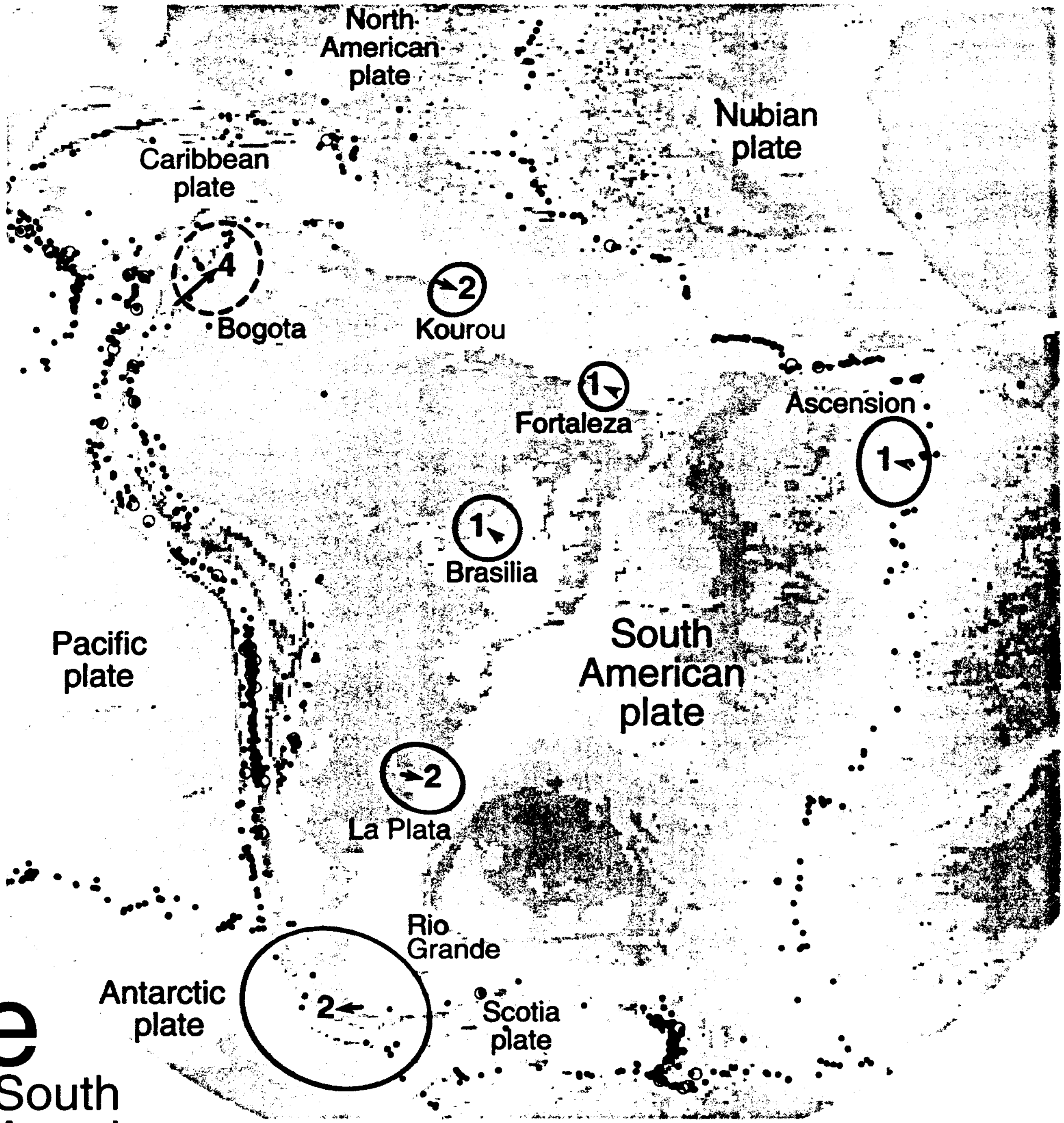
b Eurasia
Tixi
Yakutsk
Irkutsk
Krasnojarsk
Ny Alesund
North American plate
Tromso
Kiruna
Hoefn
Eurasian plate
Almaty
Bishkek
Kattakugan
Metsahovi
Mendeleevo
Onsala
Kootwijk
Potsdam
Jozefoslaw
Greenwich
Effelsberg
Borowiec
Wettzell
Zelenchukskaya
Crimea
Zimmerwald
Graz
Medicina
Sofia
Grasse
Madrid
Matera
San Fernando
Caglia
Noto
Arabian plate
Nubian plate

C

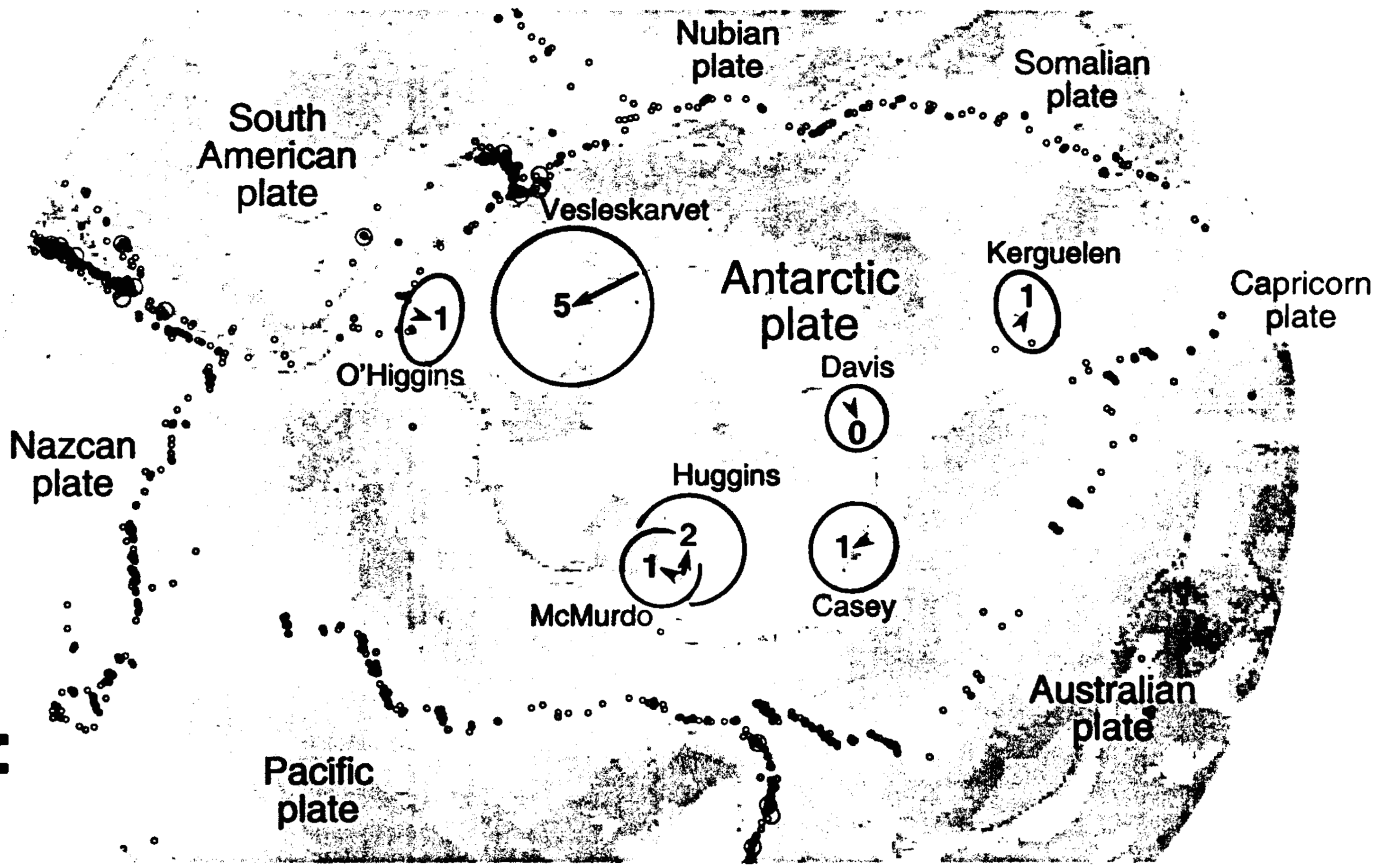

Pacific
Eurasian plate
North American plate
Vandenberg
4
4
Marcus
Kauai
Maui
0
2
2
Mauna Kea
2
Kwajalein
Cocos plate
Pacific plate
Santa Cruz
Huahine
4
4
Tahiti
Nazca plate
Australian plate
Easter
Chatam
Antarctic plate


Indian plate
Pacific plate
Diego Garcia
2
Cocos
2
Capricorn plate
Australian plate
Noumea
2
Yaragadee
Perth
2
.1
Canberra
1
0
Hobart
Auckland
2
Antarctic plate

d
Australia



e
South America

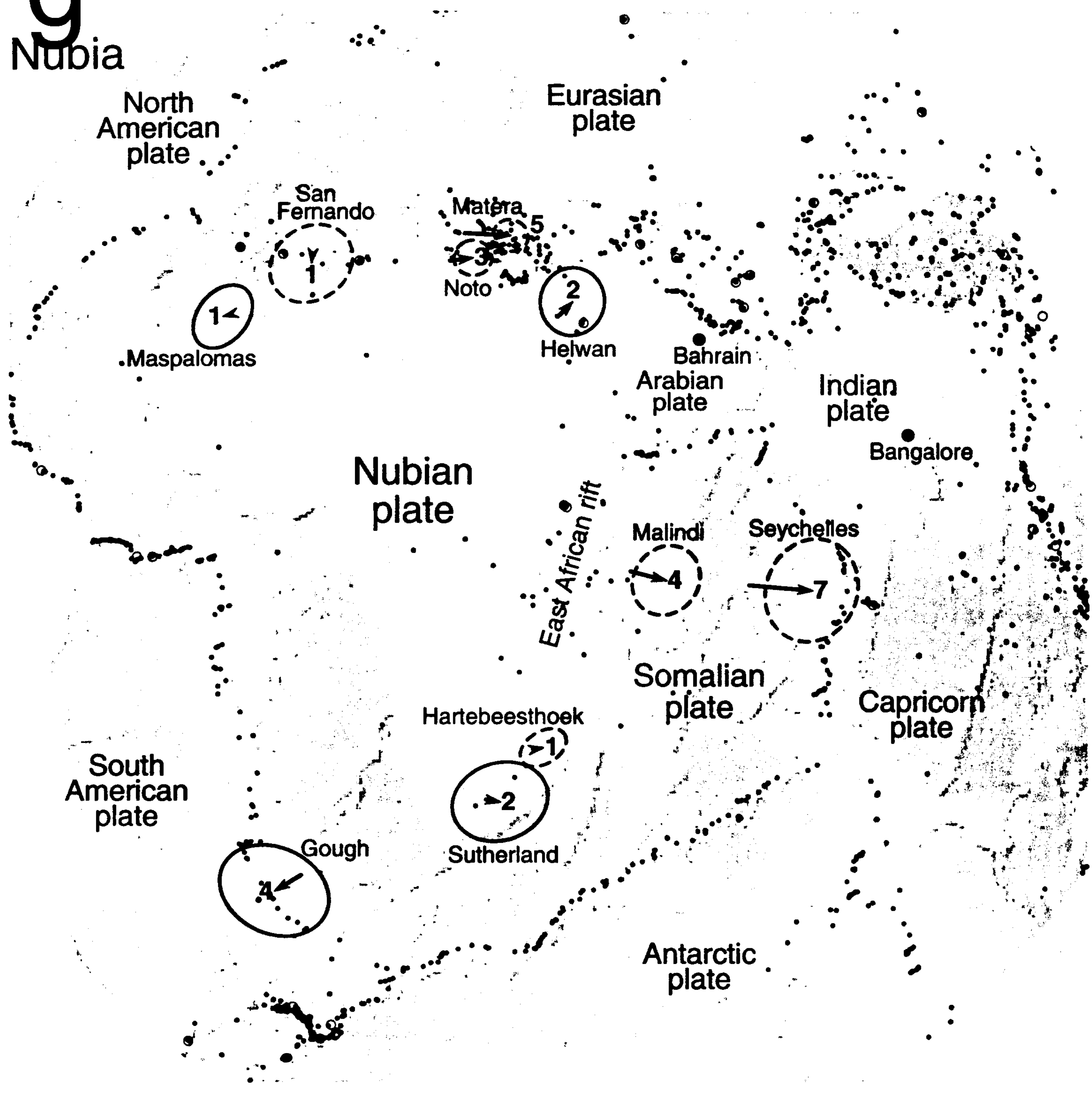


f

Antarctica

g

Nubia


North American plate
Eurasian plate
San Fernando
1
Matera
5
3
Noto
2
Helwan
1
Maspalomas
Bahrain
Arabian plate
Indian plate
Bangalore
Nubian plate
East African rift
Malindi
4
Seychelles
7
Somalian plate
Capricorn plate
Hartebeesthoek
1
2
Sutherland
South American plate
Gough
4
Antarctic plate

SCIENCE APPLICATIONS

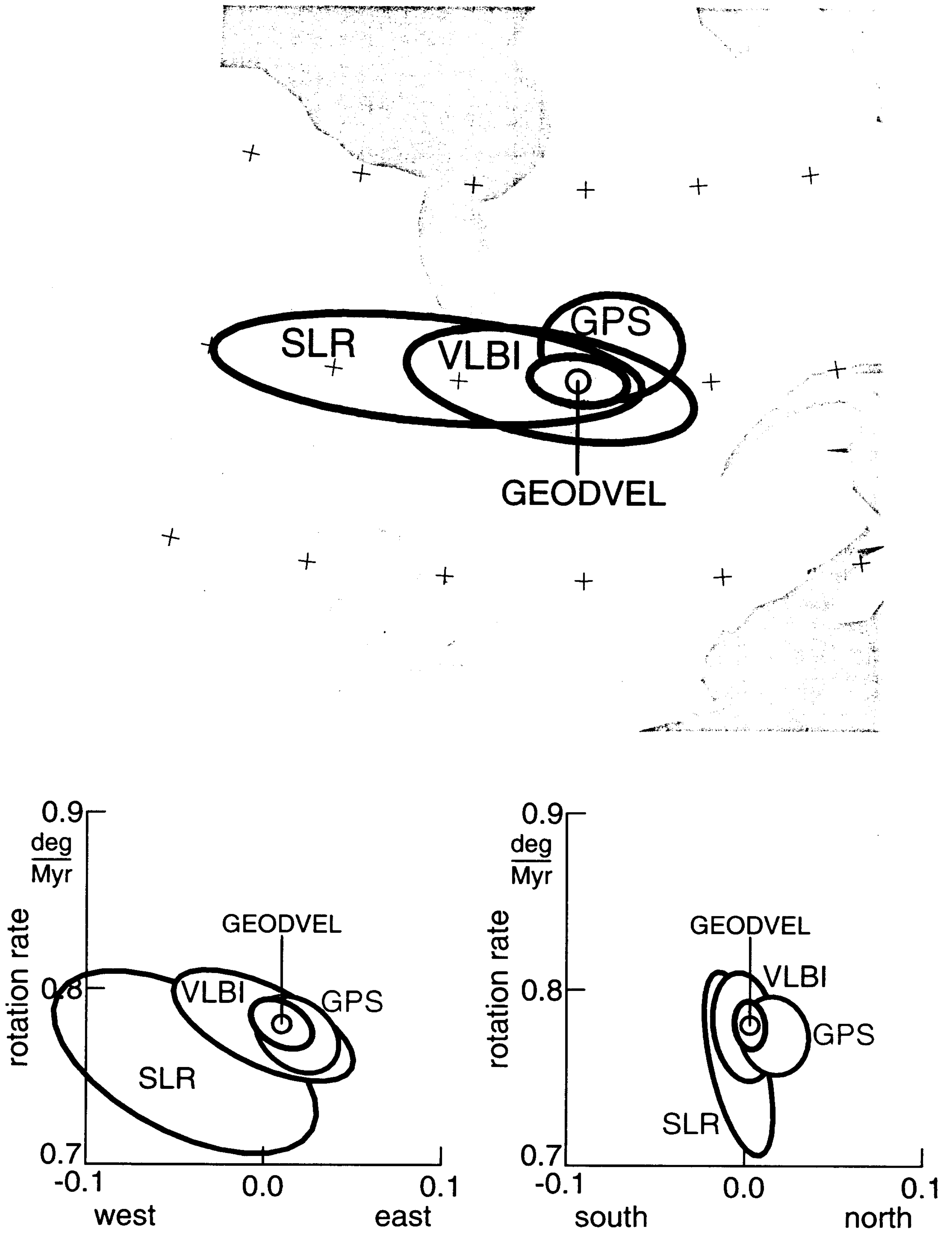
② How rigid are the plates?
Where are the limits of
the plate interiors?

Root mean square residual
~1 mm/year

Conclusion
Plates are very rigid.
Geodesy is defining
the plates limits.

PART 3
Plate Motion From Geodesy

North America–Pacific



GEODVEL

DATA

site velocities

30	VLBI	1979–1999	Ma Ryan
20	SLR	1976–2000	Eanes
104	GPS	1991–2001	Heflin
154			

PARAMETERS

angular velocities

North America
Eurasia
Pacific
Australia
South America
Nubia
Antarctica
Nazca
Somalia

horizontal velocities

Bahrain (Arabia)
Bangalore (India)

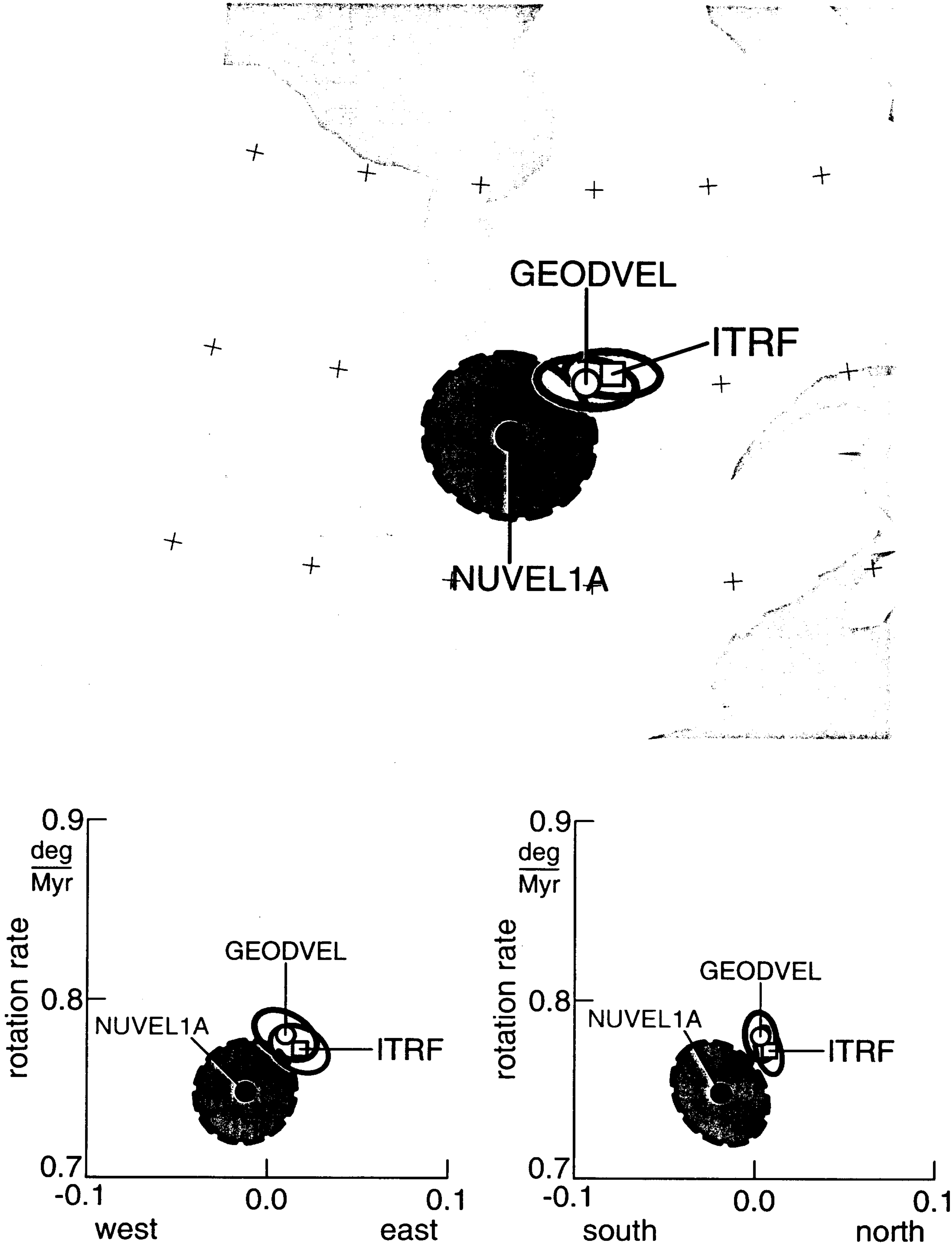
translational velocities

VLBI GPS

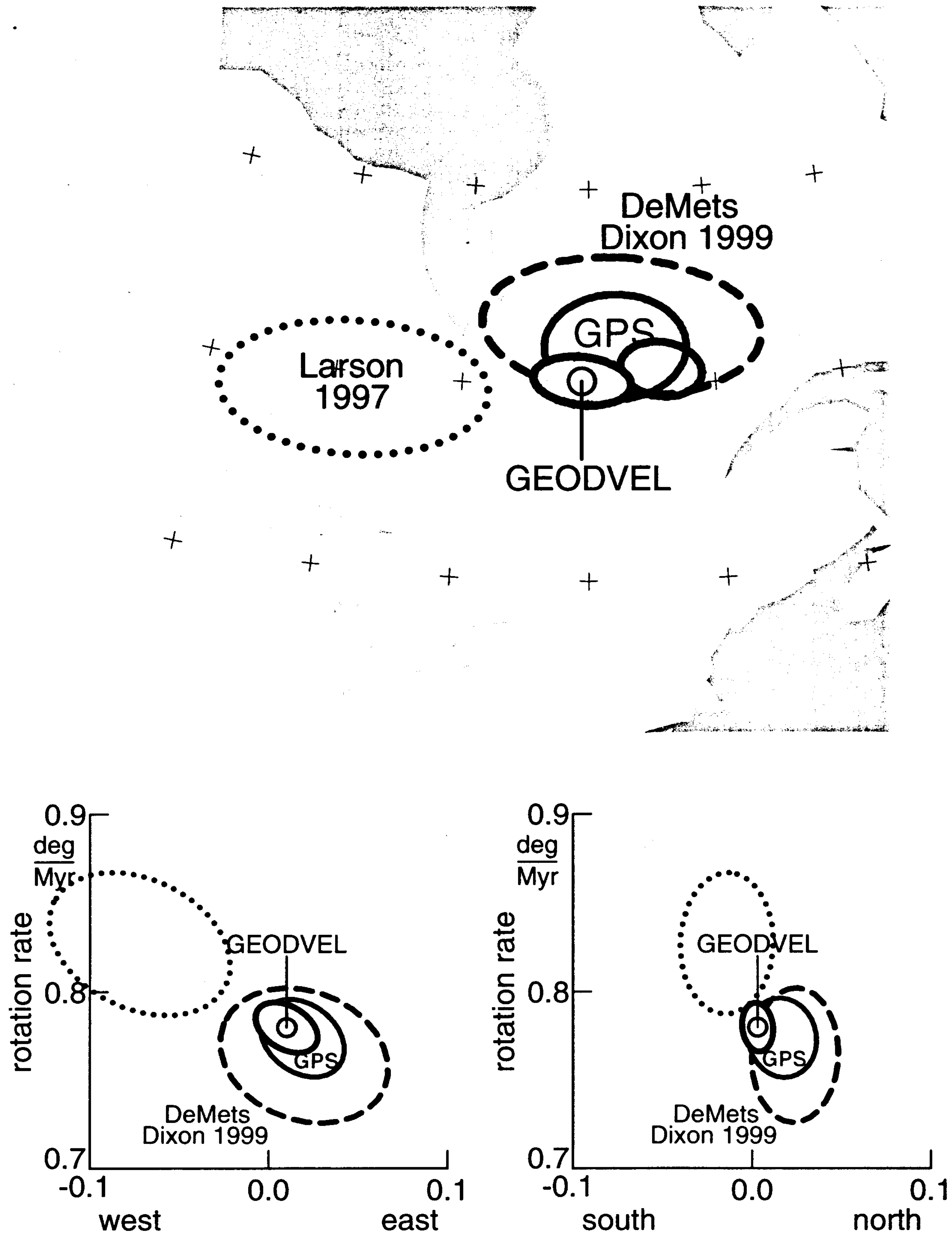
rotational velocities

VLBI SLR GPS

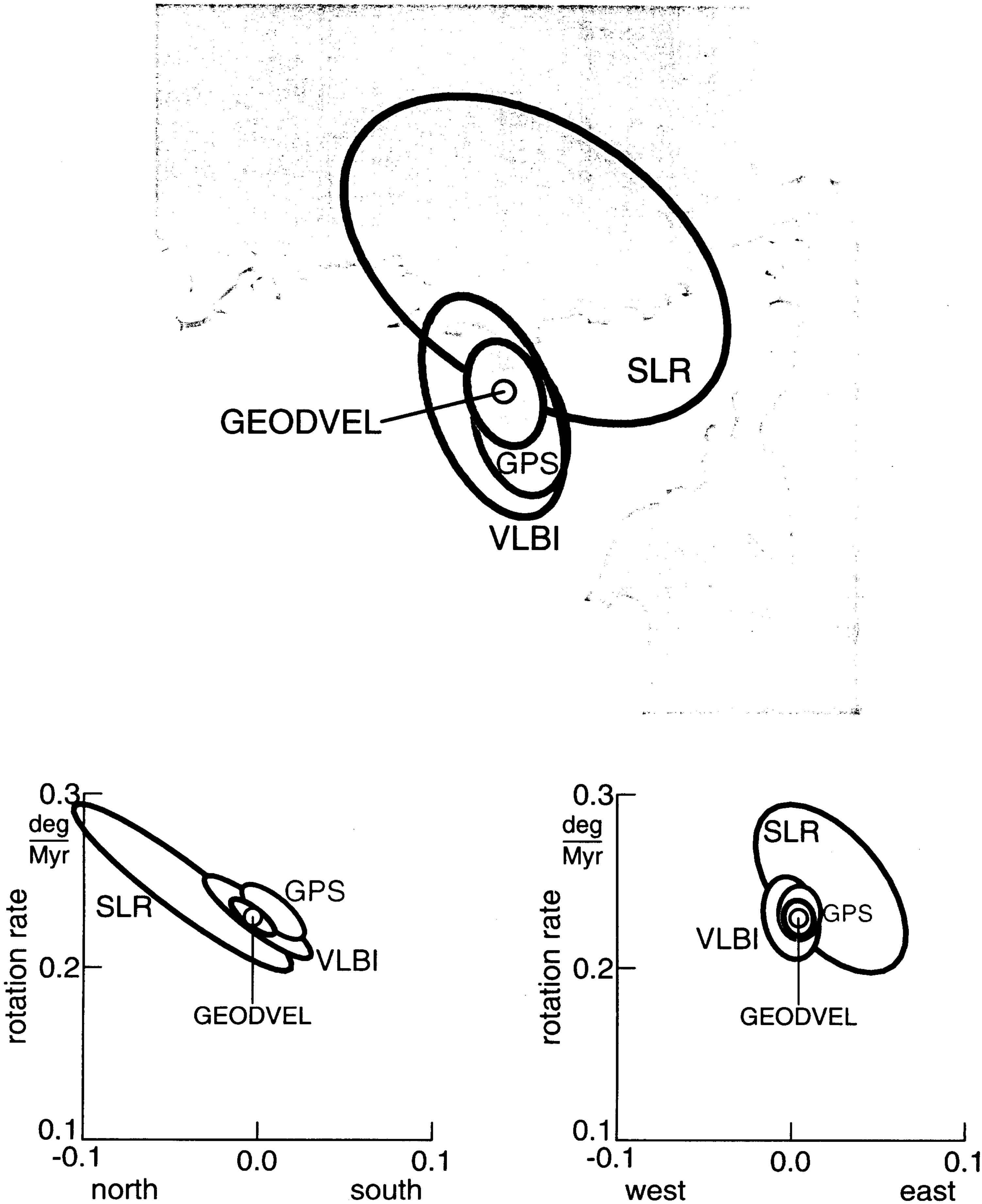
North America–Pacific



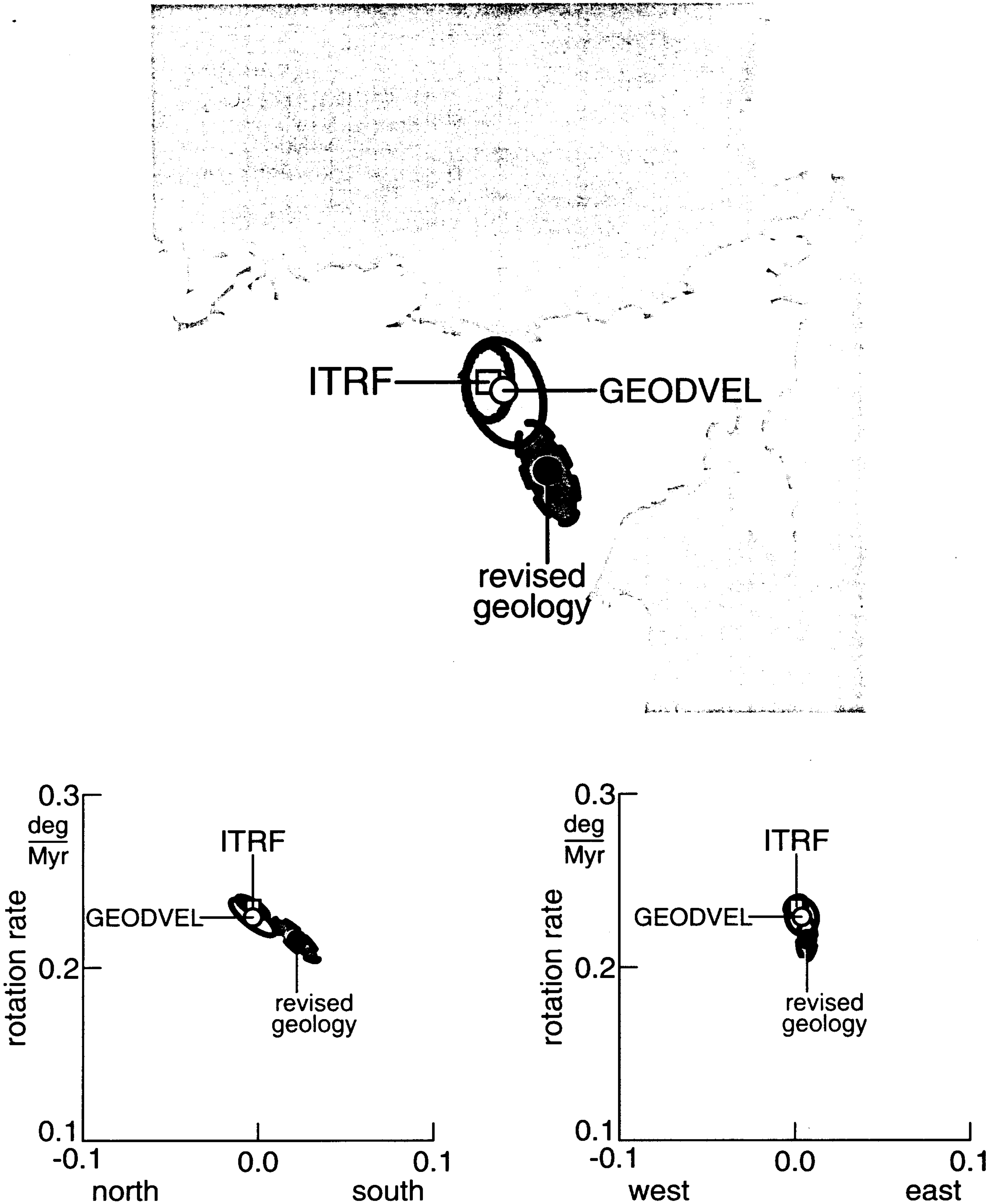
North America–Pacific



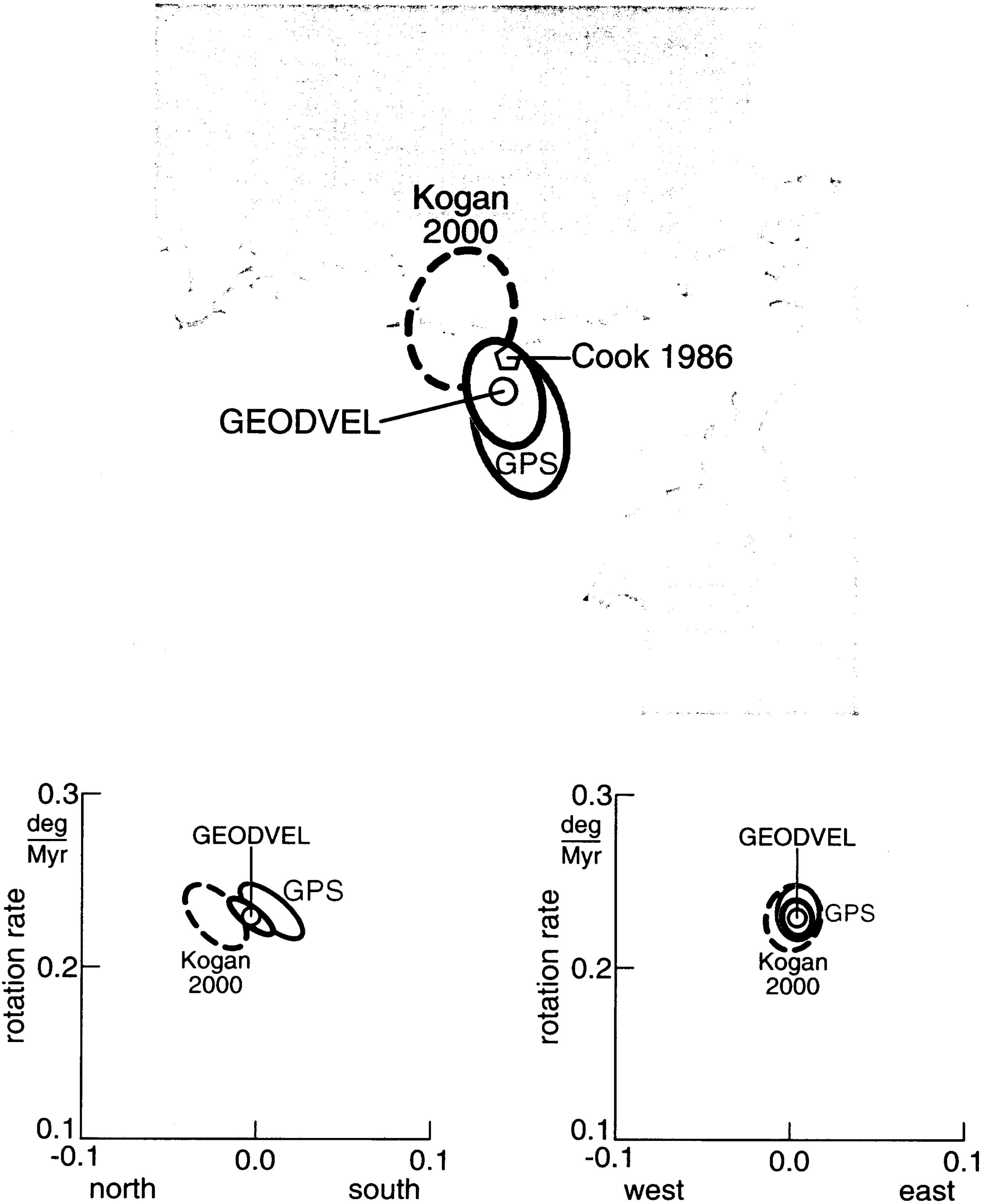
Eurasia–North America

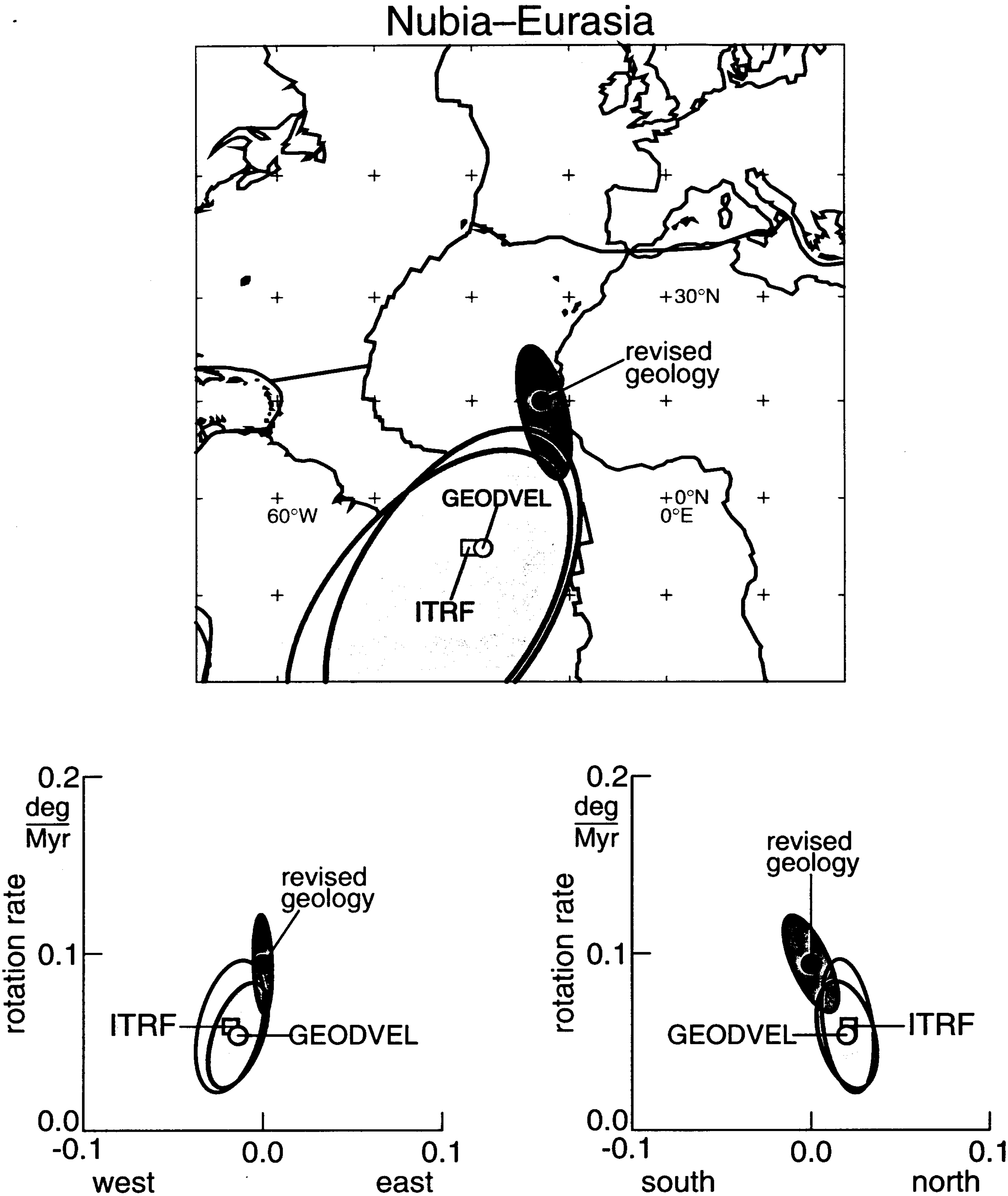


Eurasia–North America

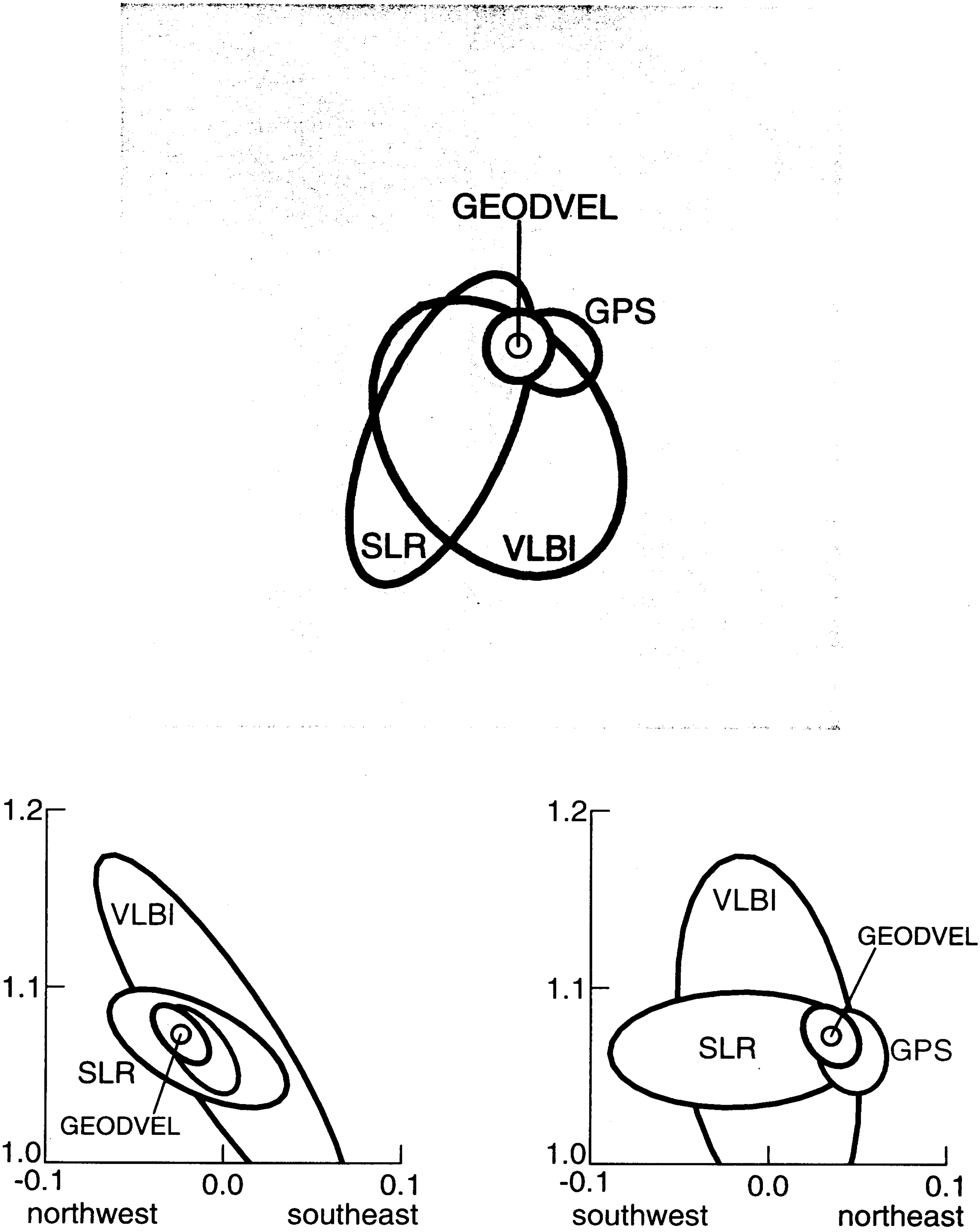


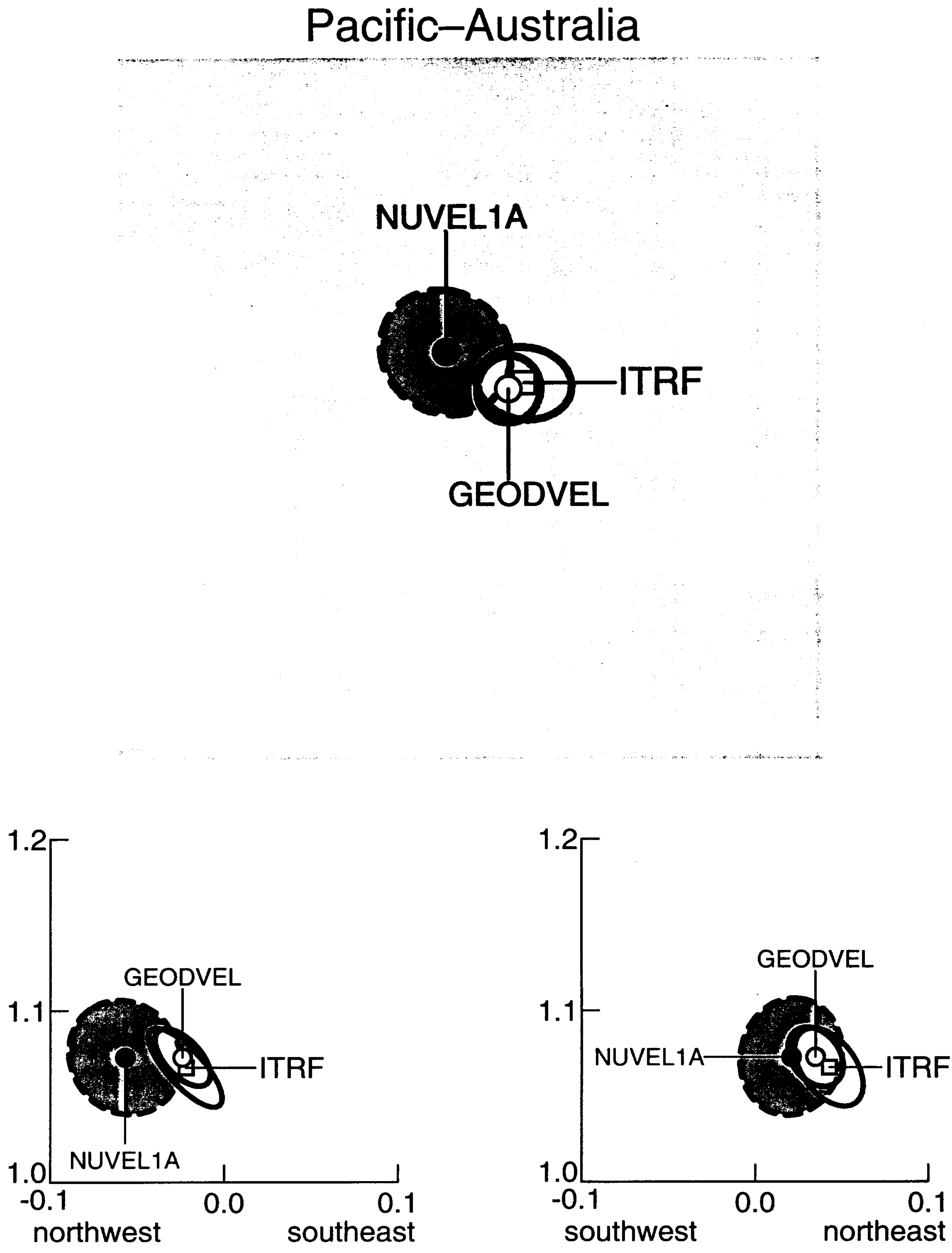
Eurasia–North America



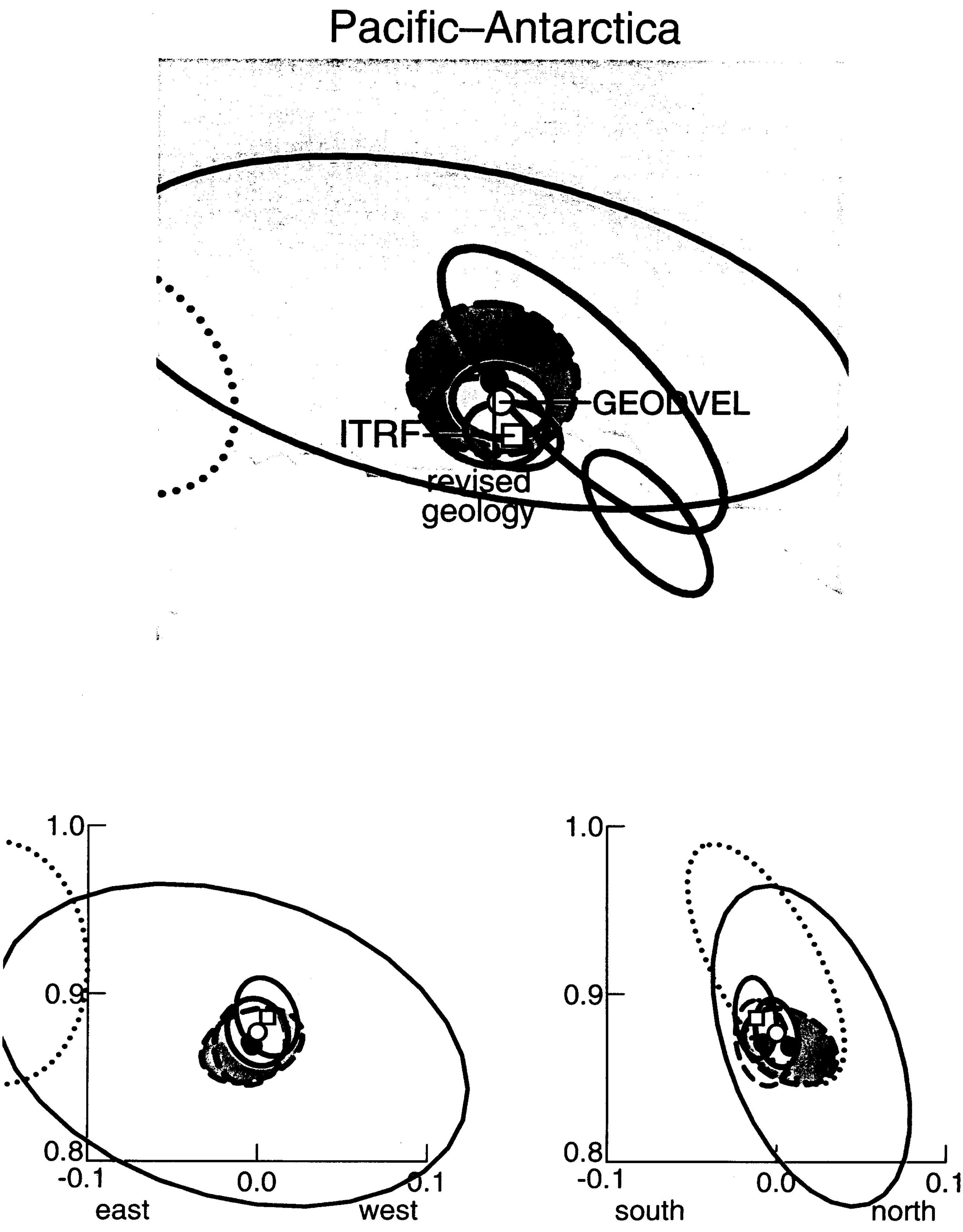

Nubia–Eurasia
+30°N
revised geology
GEODVEL
60°W
+0°N
0°E
ITRF
0.2
deg/Myr
rotation rate
0.1
0.0
-0.1
0.0
0.1
west
east
revised geology
ITRF
GEODVEL
0.2
deg/Myr
rotation rate
0.1
0.0
-0.1
0.0
0.1
south
north
revised geology
GEODVEL
ITRF

Pacific–Australia



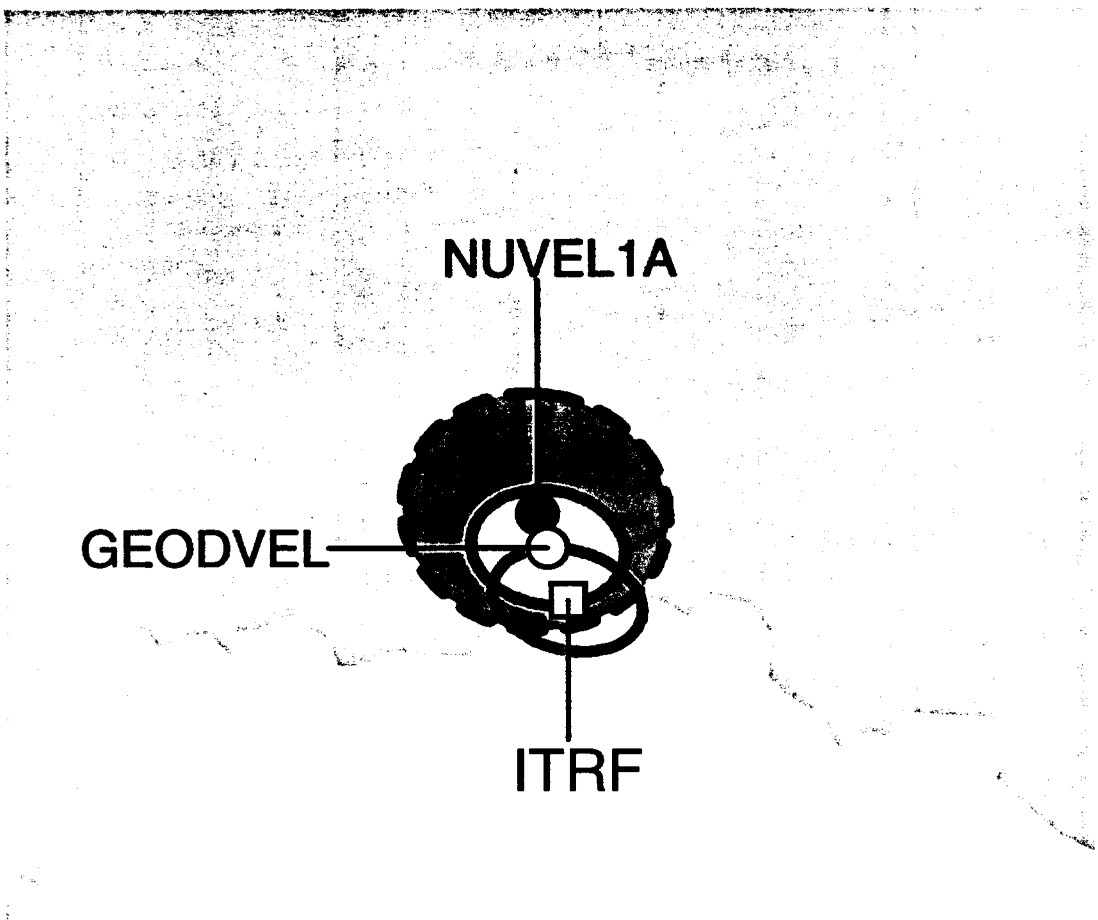


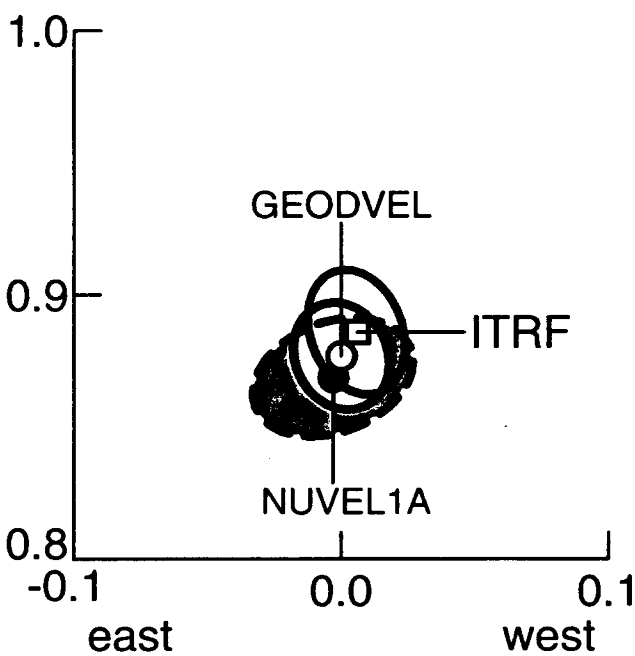
Pacific–Australia
NUVEL1A
ITRF
GEODVEL
1.2
1.1
1.0
GEODVEL
ITRF
NUVEL1A
-0.1
0.0
0.1
northwest
southeast
1.2
1.1
1.0
GEODVEL
NUVEL1A
ITRF
-0.1
0.0
0.1
southwest
northeast

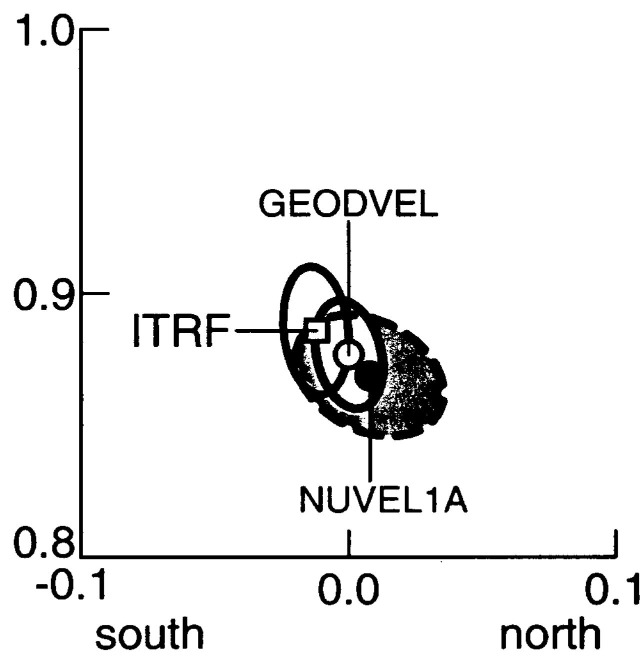


Pacific–Antarctica
GEODVEL
ITRF
revised
geology
1.0
0.9
0.8
-0.1
0.0
0.1
east
west
1.0
0.9
0.8
-0.1
0.0
0.1
south
north

Pacific–Antarctica







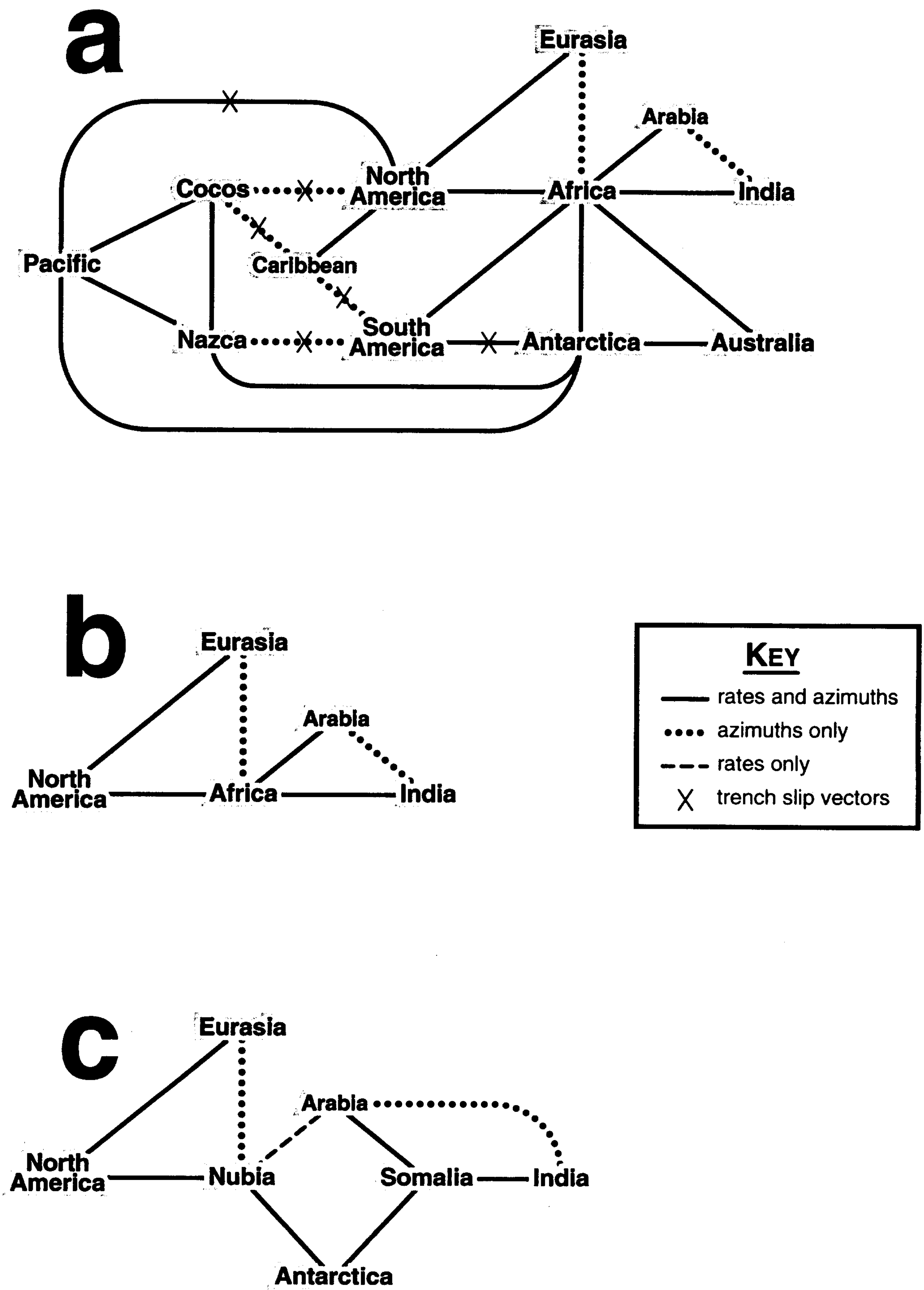
SCIENCE APPLICATIONS

③ Do plate motions from geodesy equal plate motions from geology?

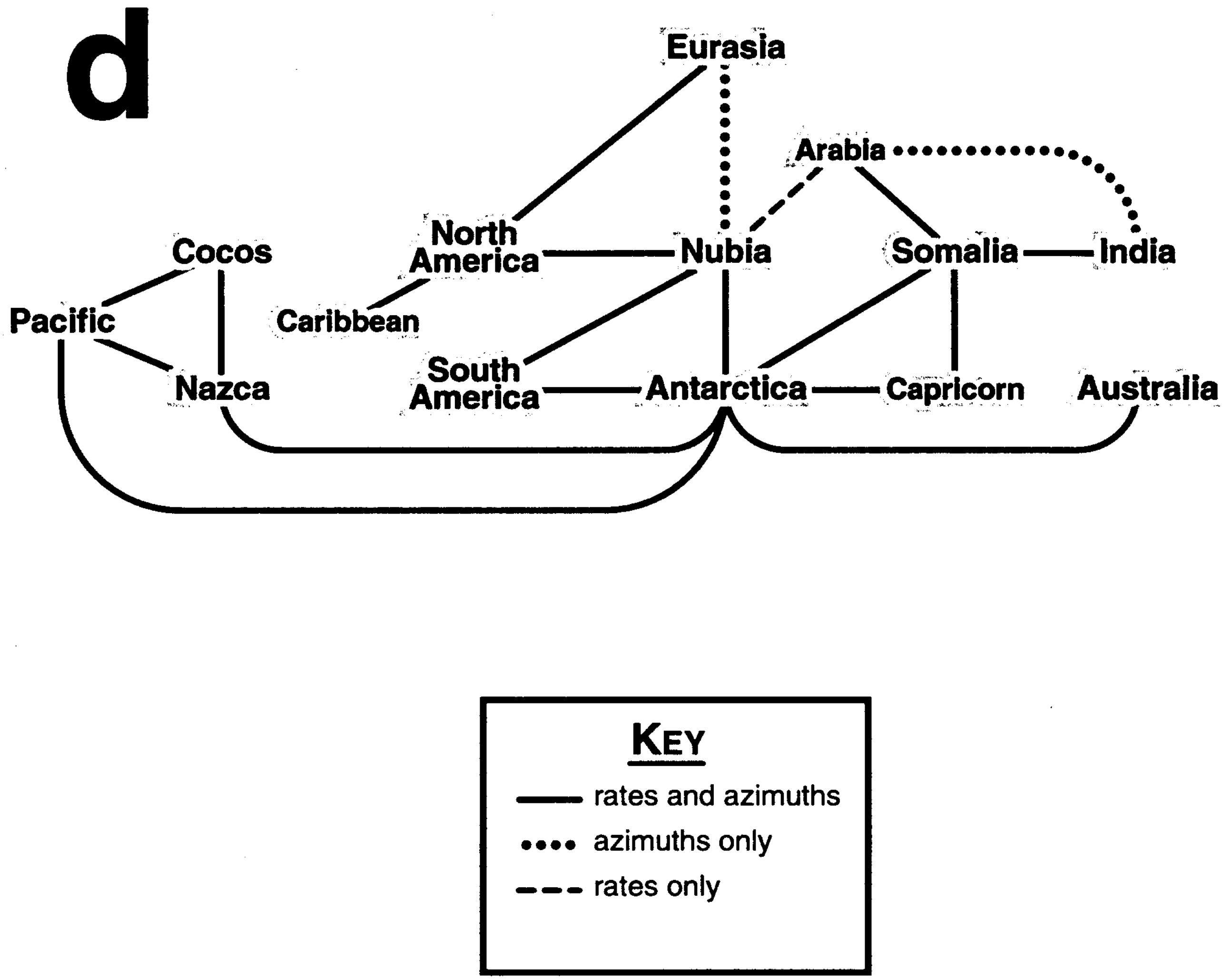
GEODVEL
 JPL GPS
 Goddard VLBI
 Texas SLR

Angular velocities
GEODVEL= ITRF2000
 more tightly constrained than before

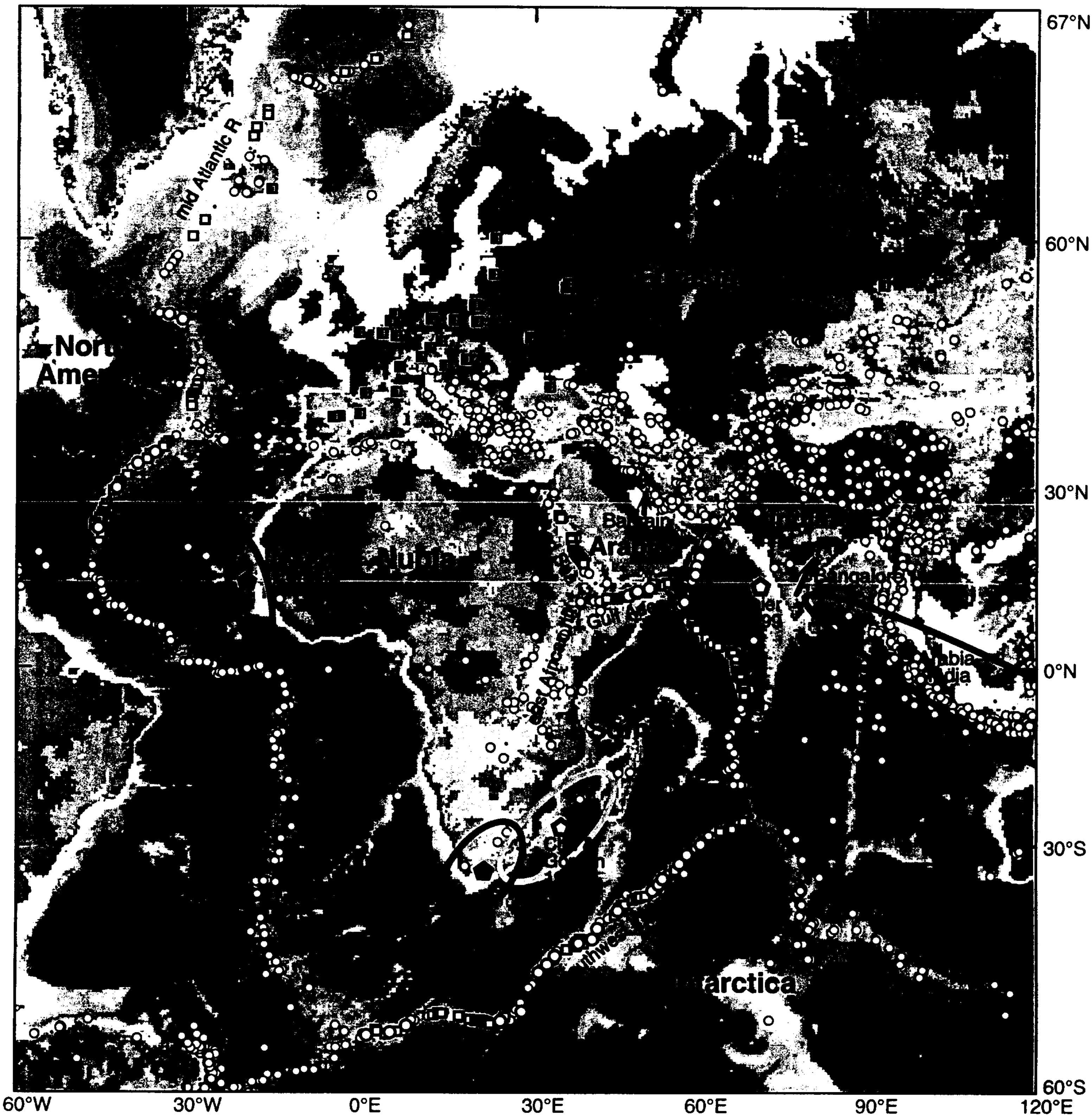
PART 4
Plate Motion From Geology



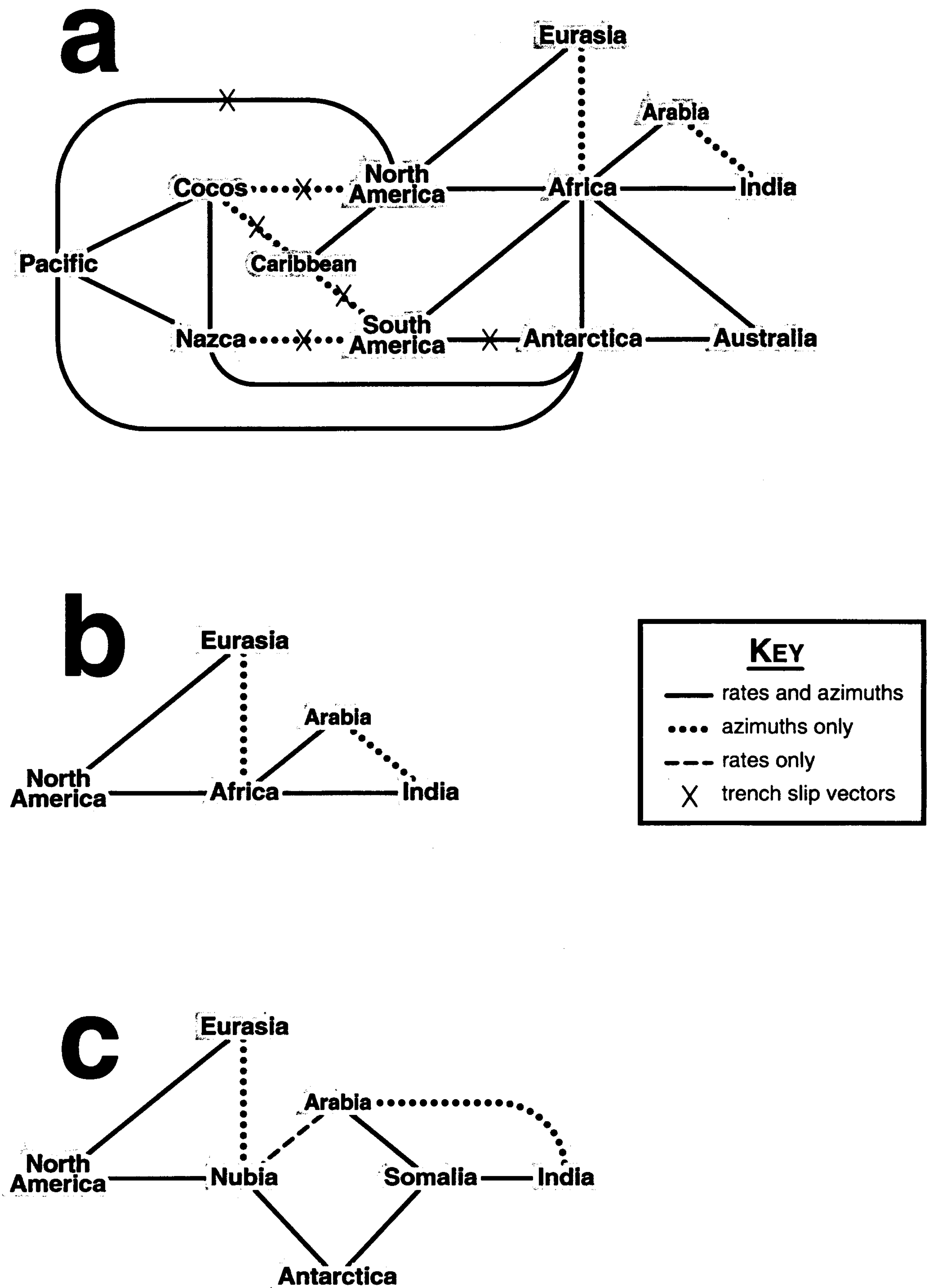
a
Eurasia
Arabia
Cocos
North America
Africa
India
Pacific
Caribbean
South America
Nazca
Antarctica
Australia
b
Eurasia
Arabia
North America
Africa
India
KEY
rates and azimuths
azimuths only
rates only
trench slip vectors
c
Eurasia
Arabia
North America
Nubia
Somalia
India
Antarctica



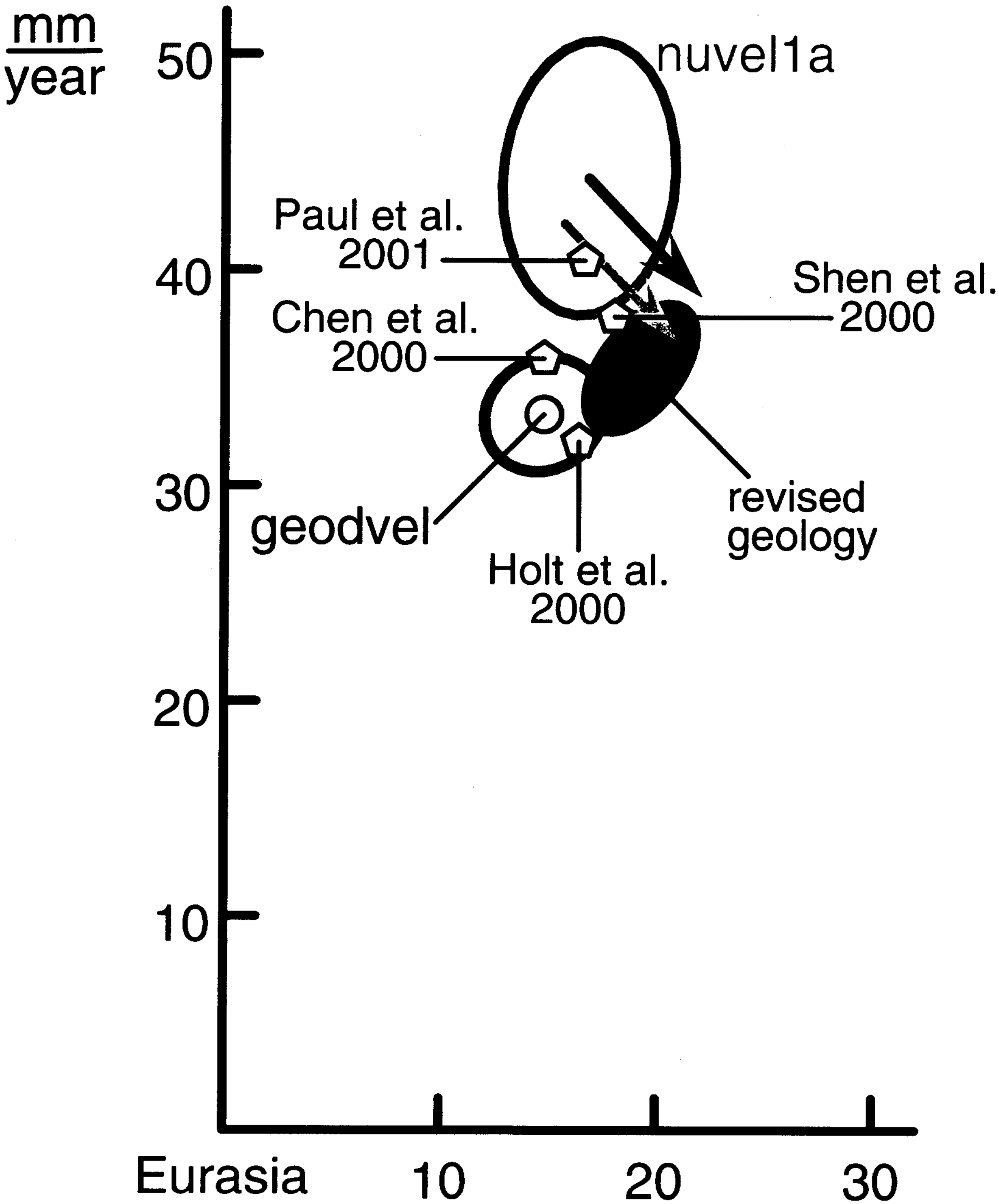
d
Eurasia
Arabia
North America
Nubia
Somalia
India
Cocos
Pacific
Caribbean
South America
Antarctica
Capricorn
Australia
Nazca
KEY
rates and azimuths
azimuths only
rates only



67°N
60°N
30°N
0°N
30°S
60°S
60°W
30°W
0°E
30°E
60°E
90°E
120°E
mid Atlantic R
Nubia
Bangalore


a
Eurasia
Arabia
Cocos
North America
Africa
India
Pacific
Caribbean
South America
Nazca
Antarctica
Australia
b
Eurasia
Arabia
North America
Africa
India
KEY
rates and azimuths
azimuths only
rates only
trench slip vectors
c
Eurasia
Arabia
North America
Nubia
Somalia
India
Antarctica

Bangalore (India)



SCIENCE APPLICATIONS

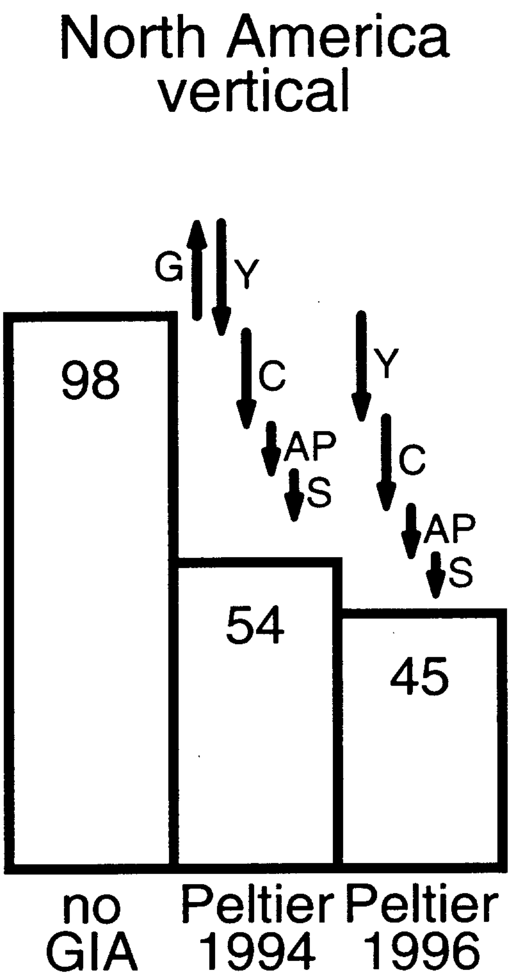
④ Do plate motions from geodesy equal plate motions from geology?

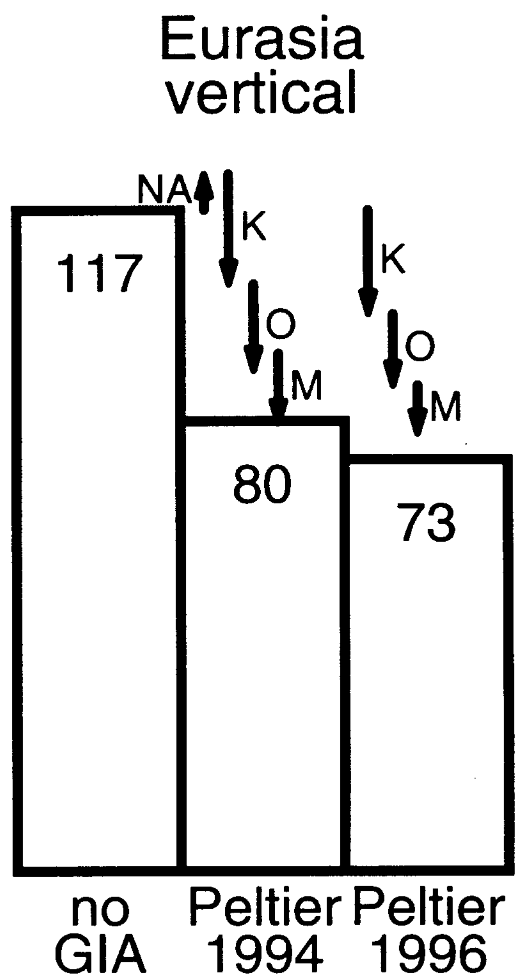
NUVEL1A shortcoming
- neglects motion across east African rift
- motion between Pacific plates and surrounding continental plates screwed up

Conclusion
- Space geodesy is becoming more accurate than geology.

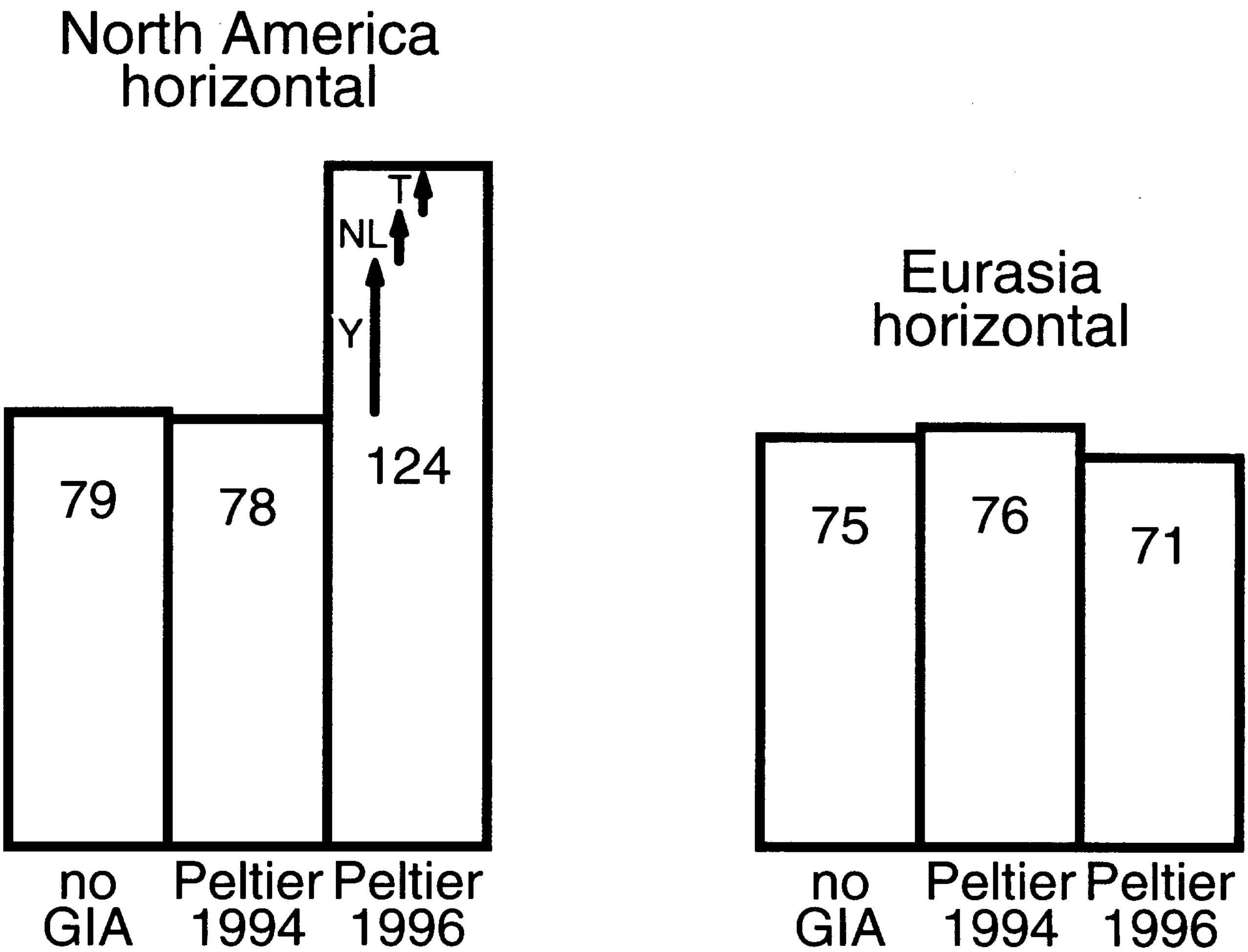
PART 5
Postglacial Rebound

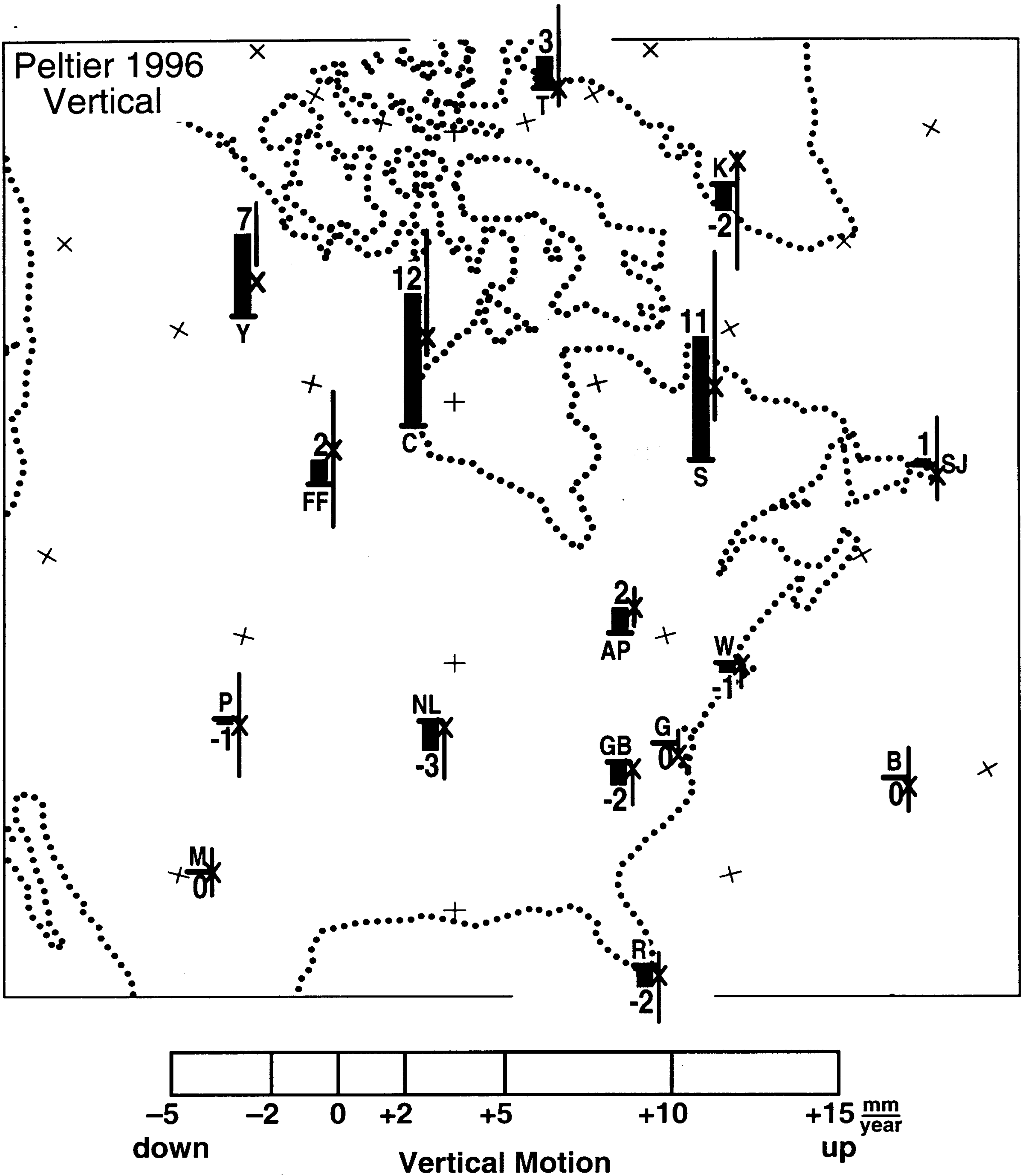
Misfit

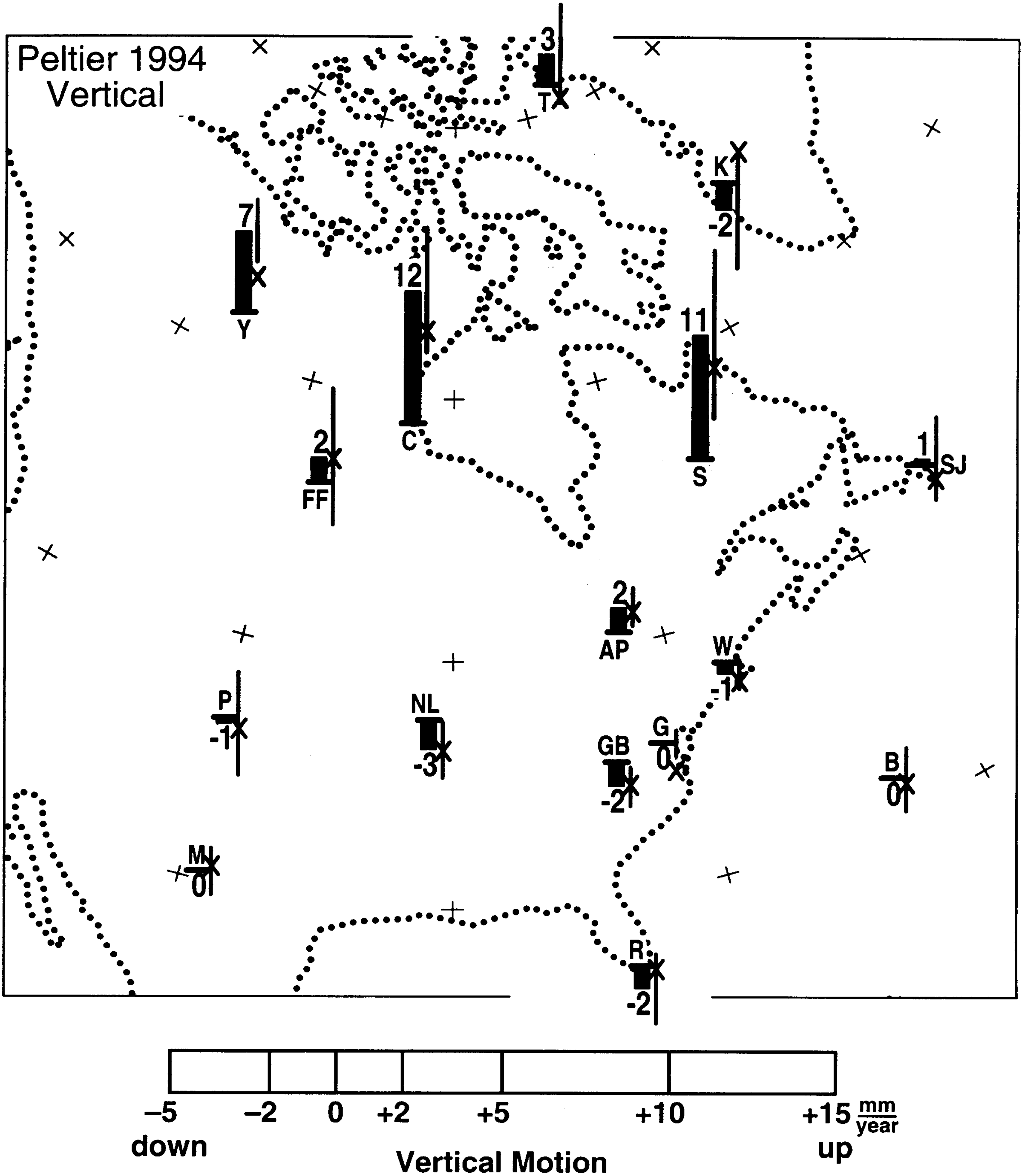

North America
vertical
98
54
45
G
Y
C
AP
S
Y
C
AP
S
no GIA
Peltier 1994
Peltier 1996

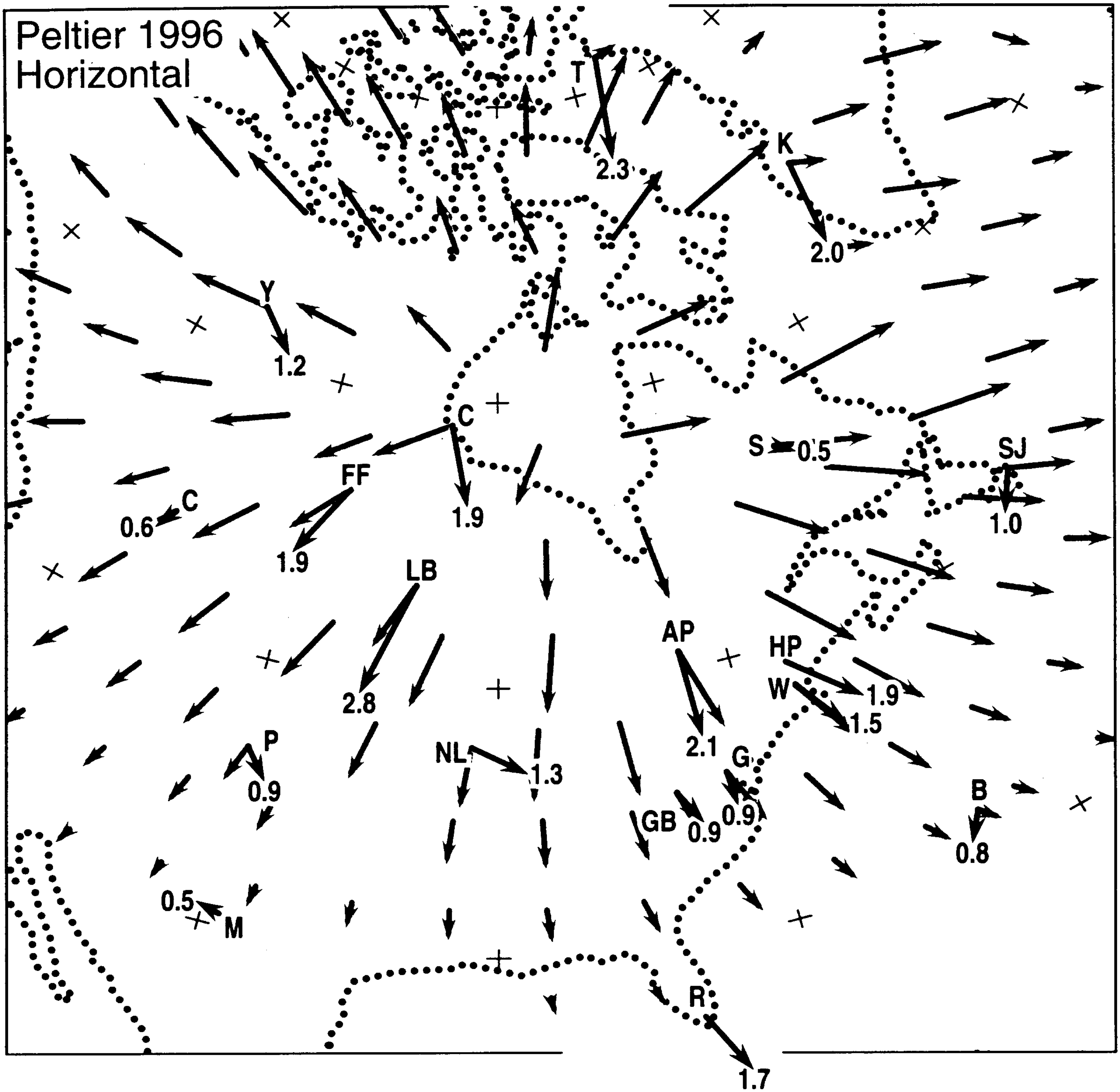

Eurasia
vertical
117
80
73
NA
K
O
M
K
O
M
no GIA
Peltier 1994
Peltier 1996

Misfit

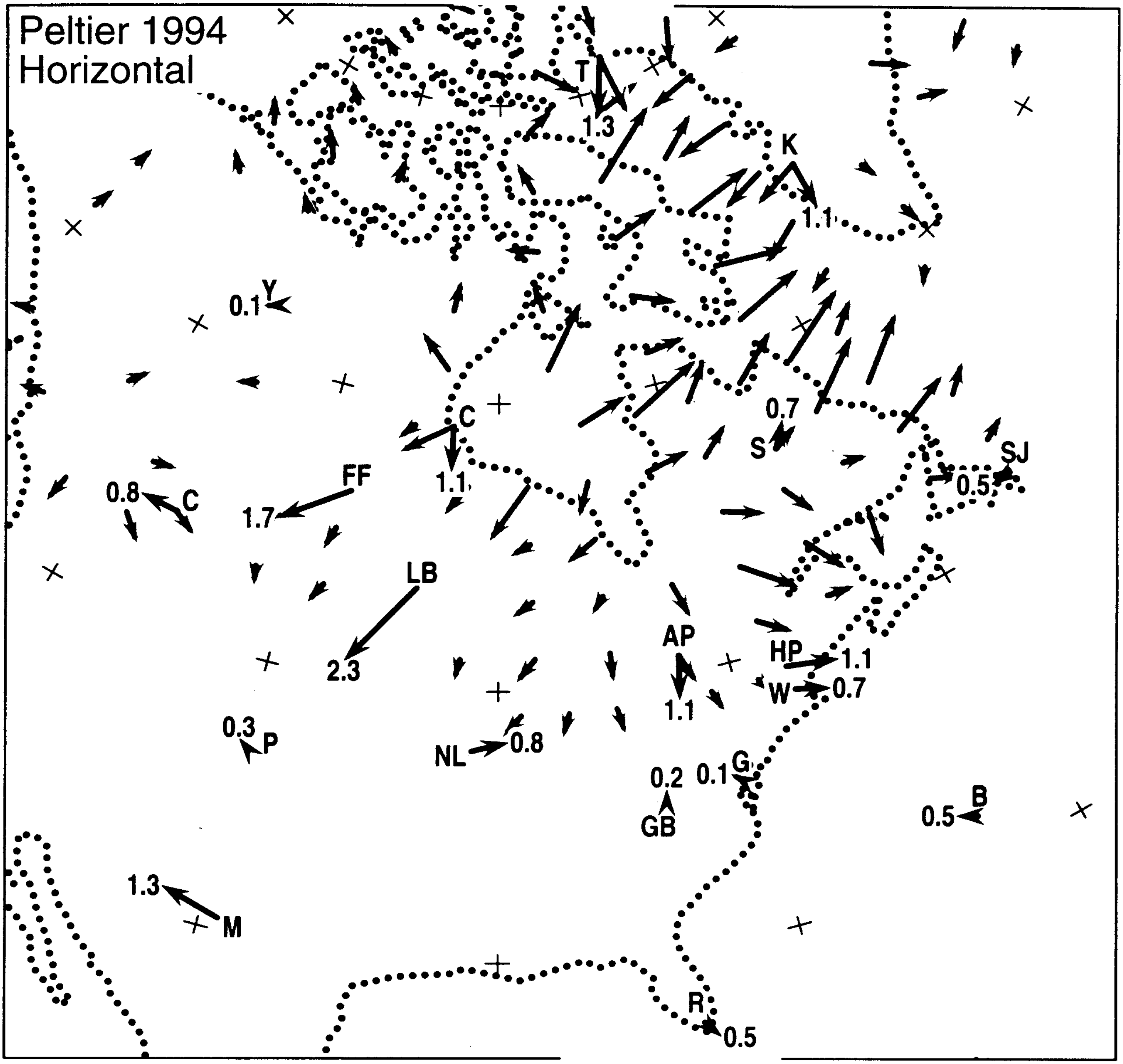

North America horizontal
79
78
124
Y
NL
T
no GIA
Peltier 1994
Peltier 1996
Eurasia horizontal
75
76
71
no GIA
Peltier 1994
Peltier 1996

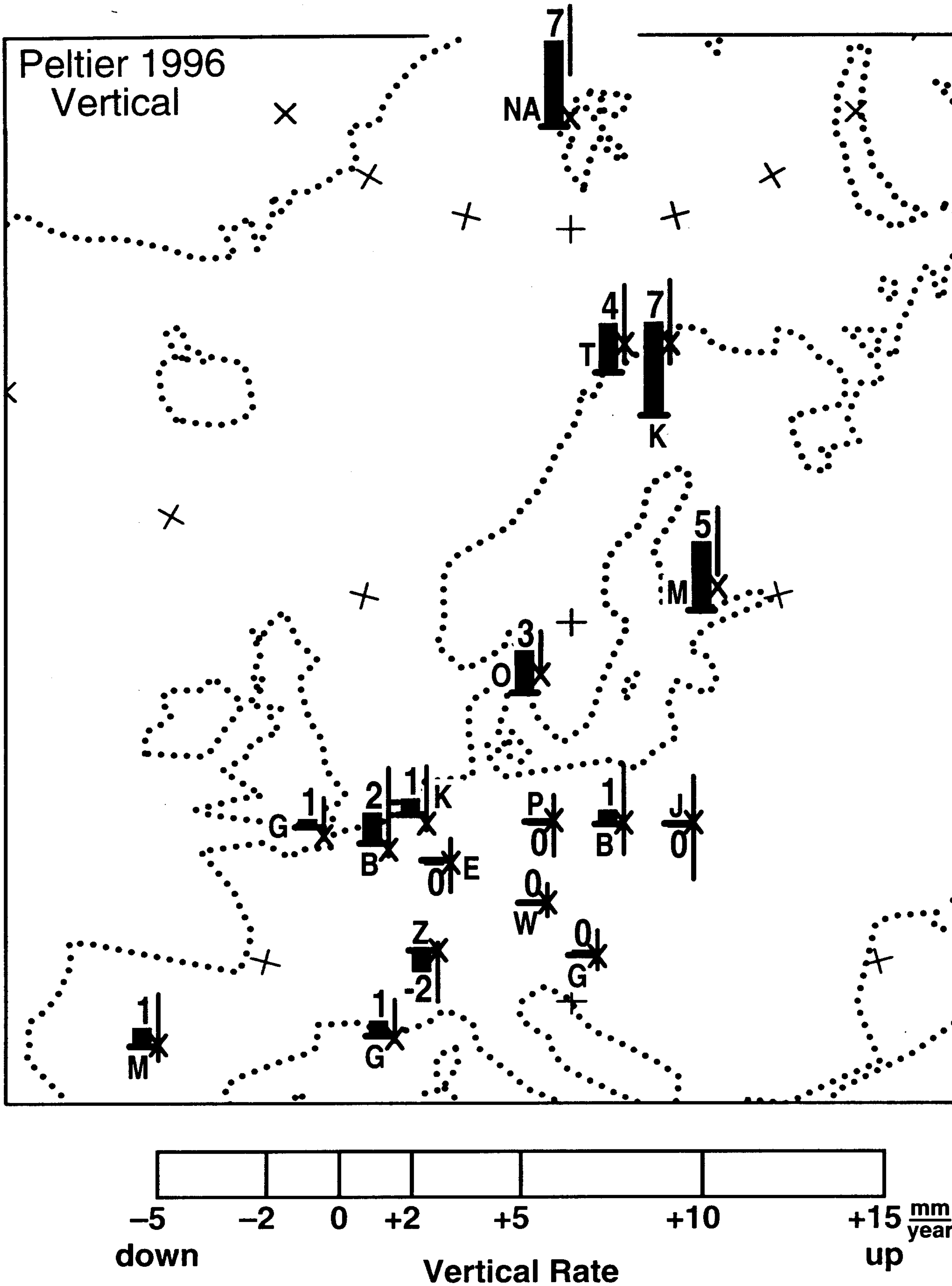

Peltier 1996
Vertical
3
T
K
-2
7
Y
12
C
11
S
2
FF
1
SJ
2
AP
W
-1
P
-1
NL
-3
G
0
GB
-2
B
0
M
0
R
-2
–5
–2
0
+2
+5
+10
+15
mm
year
down
up
Vertical Motion


Peltier 1994
Vertical
3
T
K
-2
7
Y
12
C
11
S
2
FF
1
SJ
2
AP
W
-1
P
-1
NL
-3
GB
-2
G
0
B
0
M
0
R
-2
−5
−2
0
+2
+5
+10
+15
mm
year
down
up
Vertical Motion

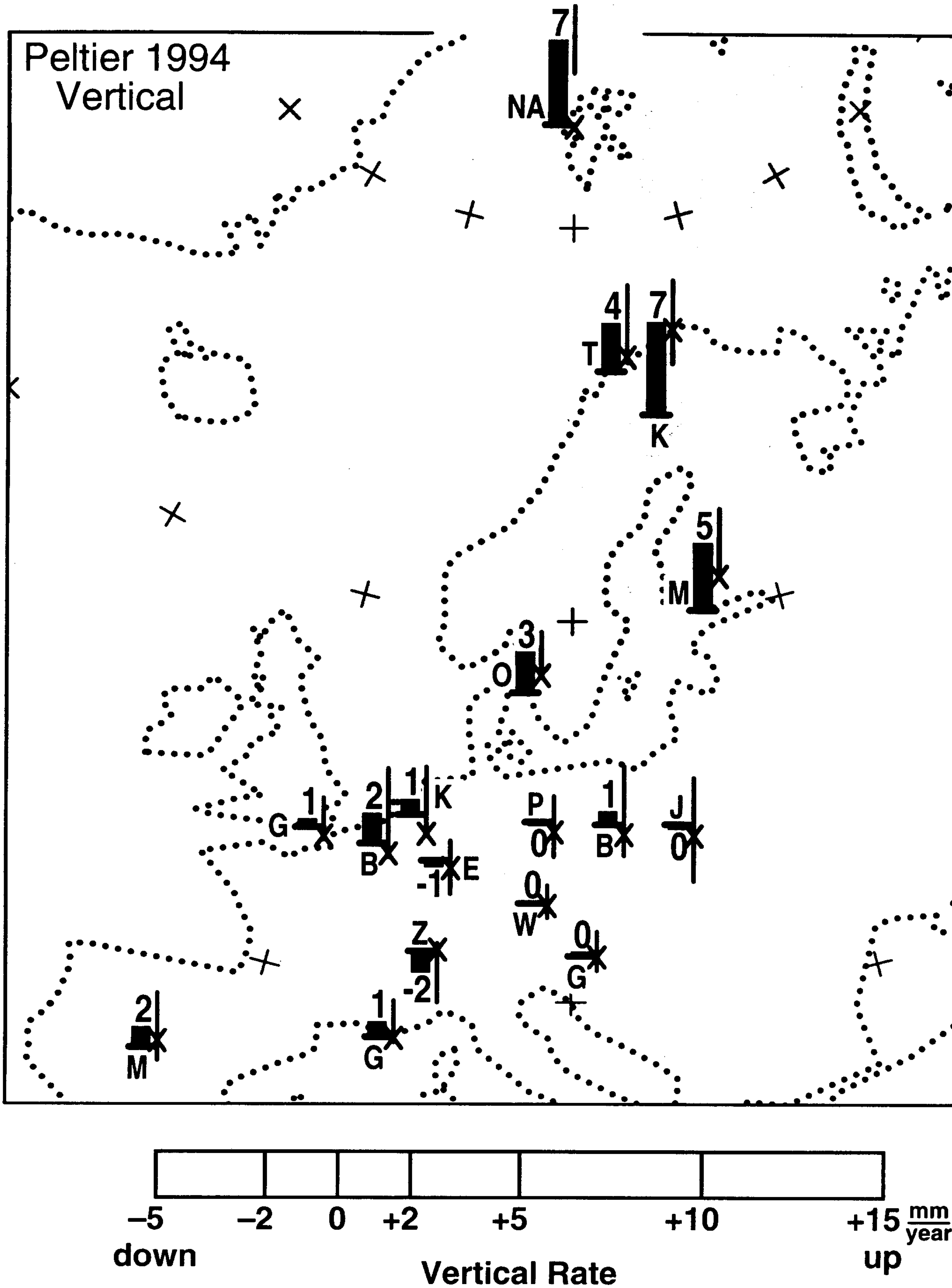


Peltier 1996
Horizontal
T
2.3
K
2.0
Y
1.2
C
S
0.5
SJ
1.0
FF
1.9
C
0.6
1.9
LB
2.8
AP
2.1
HP
1.9
W
1.5
G
0.9
GB
0.9
P
0.9
NL
1.3
B
0.8
0.5
M
R
1.7

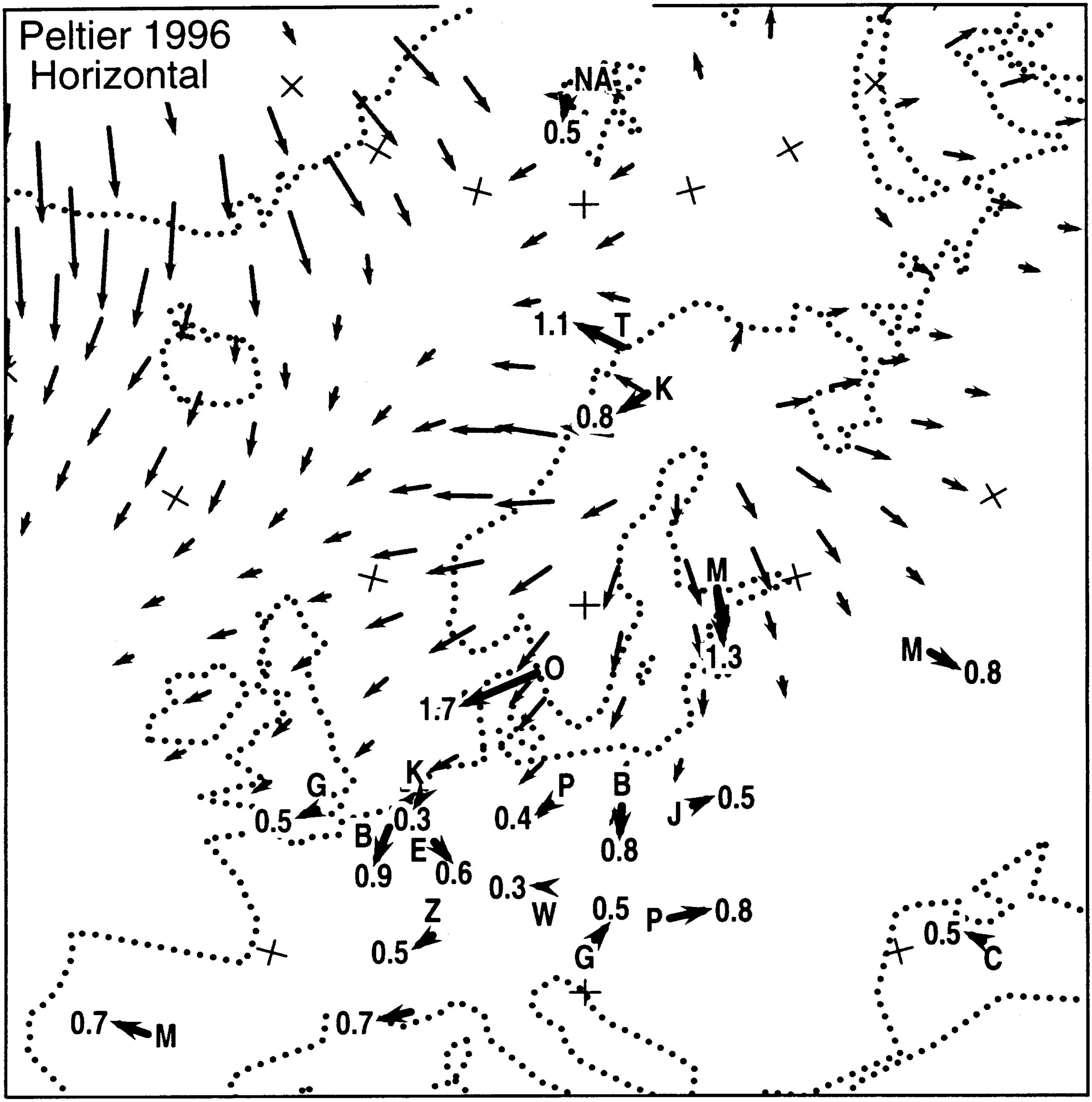

Peltier 1994
Horizontal
T
1.3
K
1.1
Y
0.1
C
1.1
0.7
S
SJ
0.5
0.8
C
FF
1.7
LB
2.3
AP
1.1
HP
1.1
W
0.7
0.3
P
NL
0.8
0.2
GB
0.1
G
B
0.5
1.3
M
R
0.5

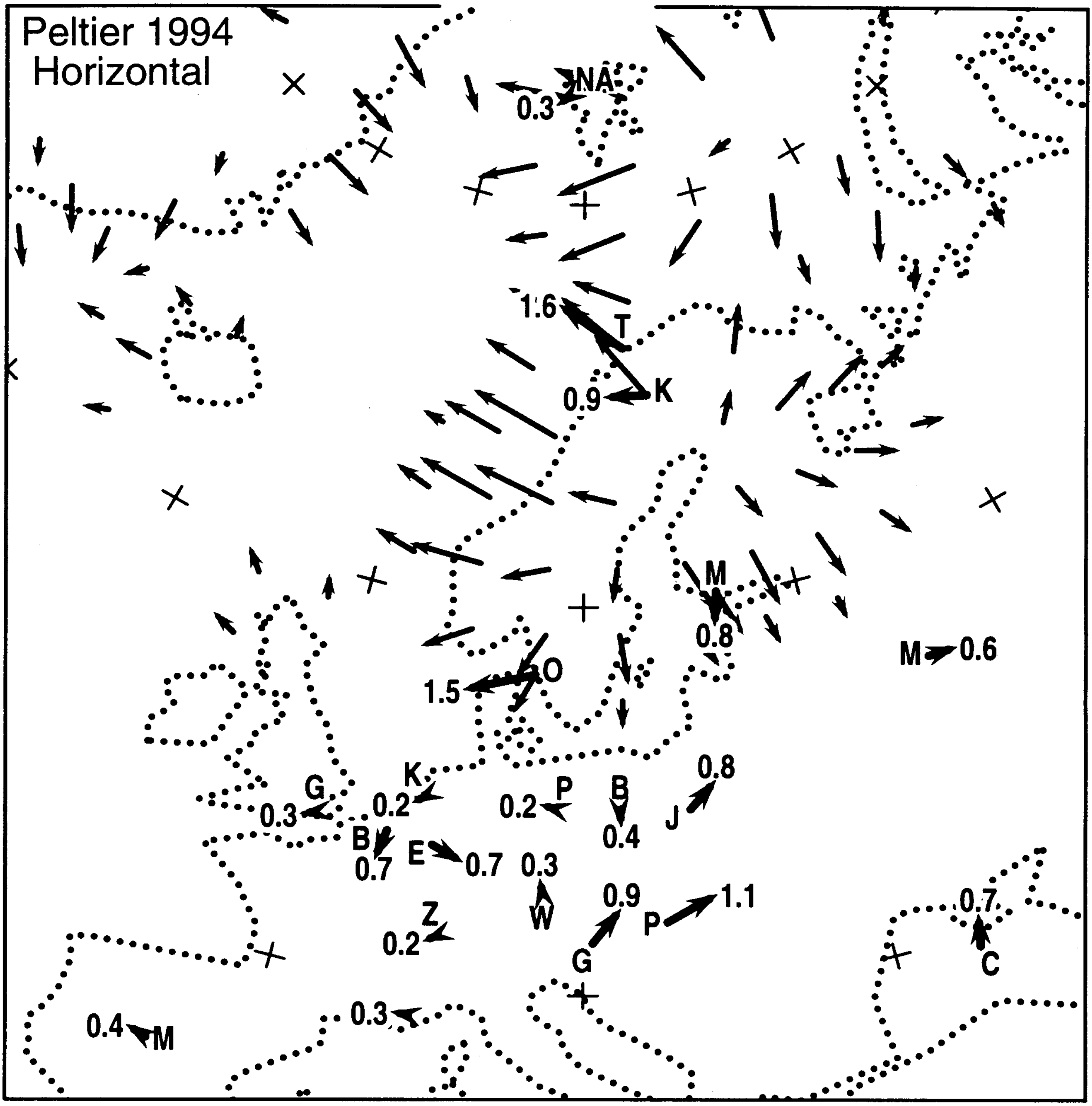


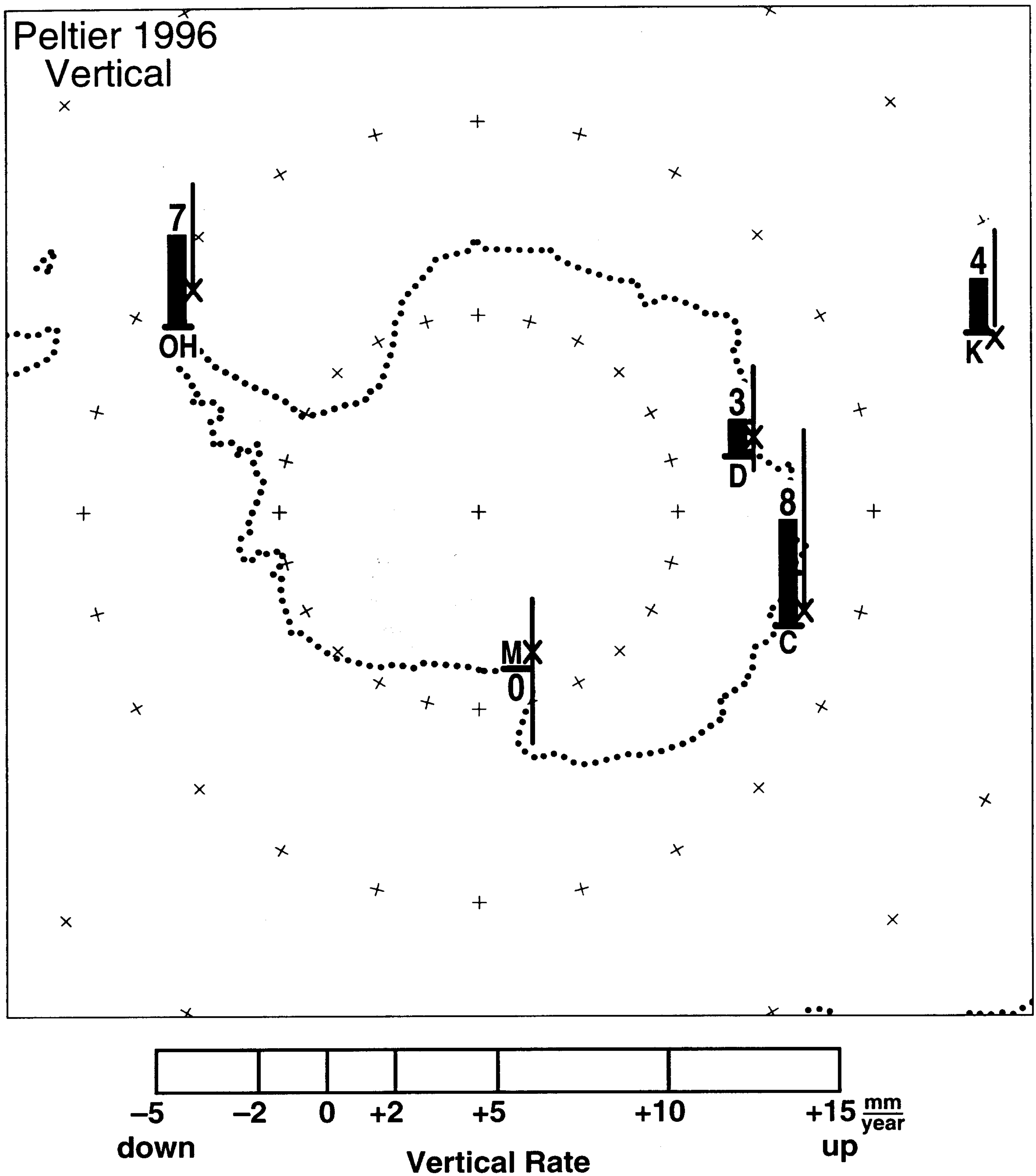
Peltier 1996
Vertical
7
NA
4
7
T
K
5
M
3
O
1
G
2
B
1
K
E
0
P
0
1
B
J
0
0
W
Z
-2
0
G
1
M
1
G
–5
–2
0
+2
+5
+10
+15 mm/year
down
up
Vertical Rate



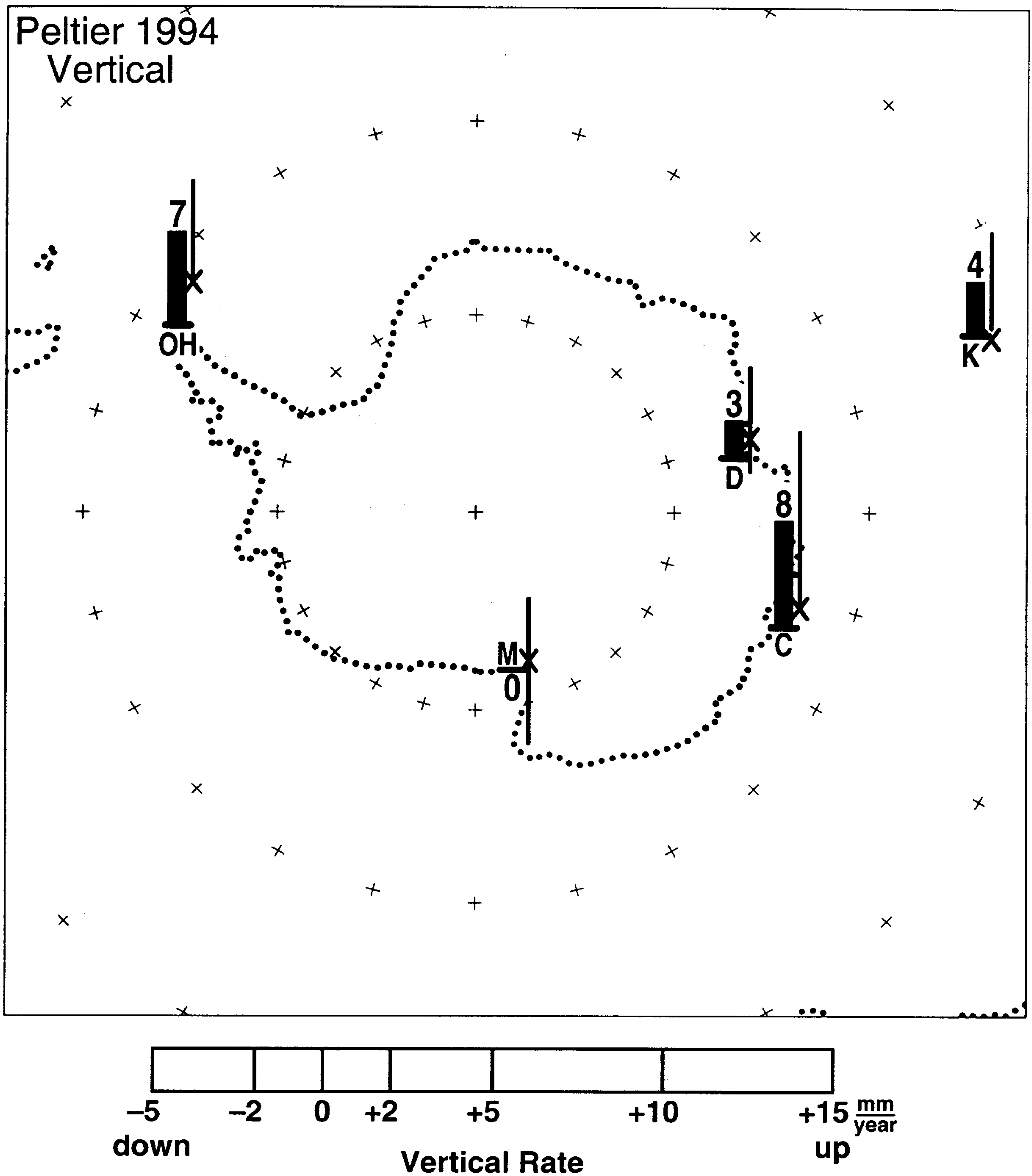
Peltier 1994
Vertical
7
NA
4
T
7
K
5
M
3
O
1
G
2
B
1
K
P
0
1
B
J
0
-1
E
0
W
Z
-2
0
G
2
M
1
G
-5
down
-2
0
+2
+5
+10
+15 mm/year
up
Vertical Rate


Peltier 1996
Horizontal
NA
0.5
1.1
T
K
0.8
M
1.3
M
0.8
O
1.7
K
G
0.5
0.3
P
0.4
B
0.8
J
0.5
B
0.9
E
0.6
0.3
W
Z
0.5
0.5
G
P
0.8
0.5
C
0.7
M
0.7

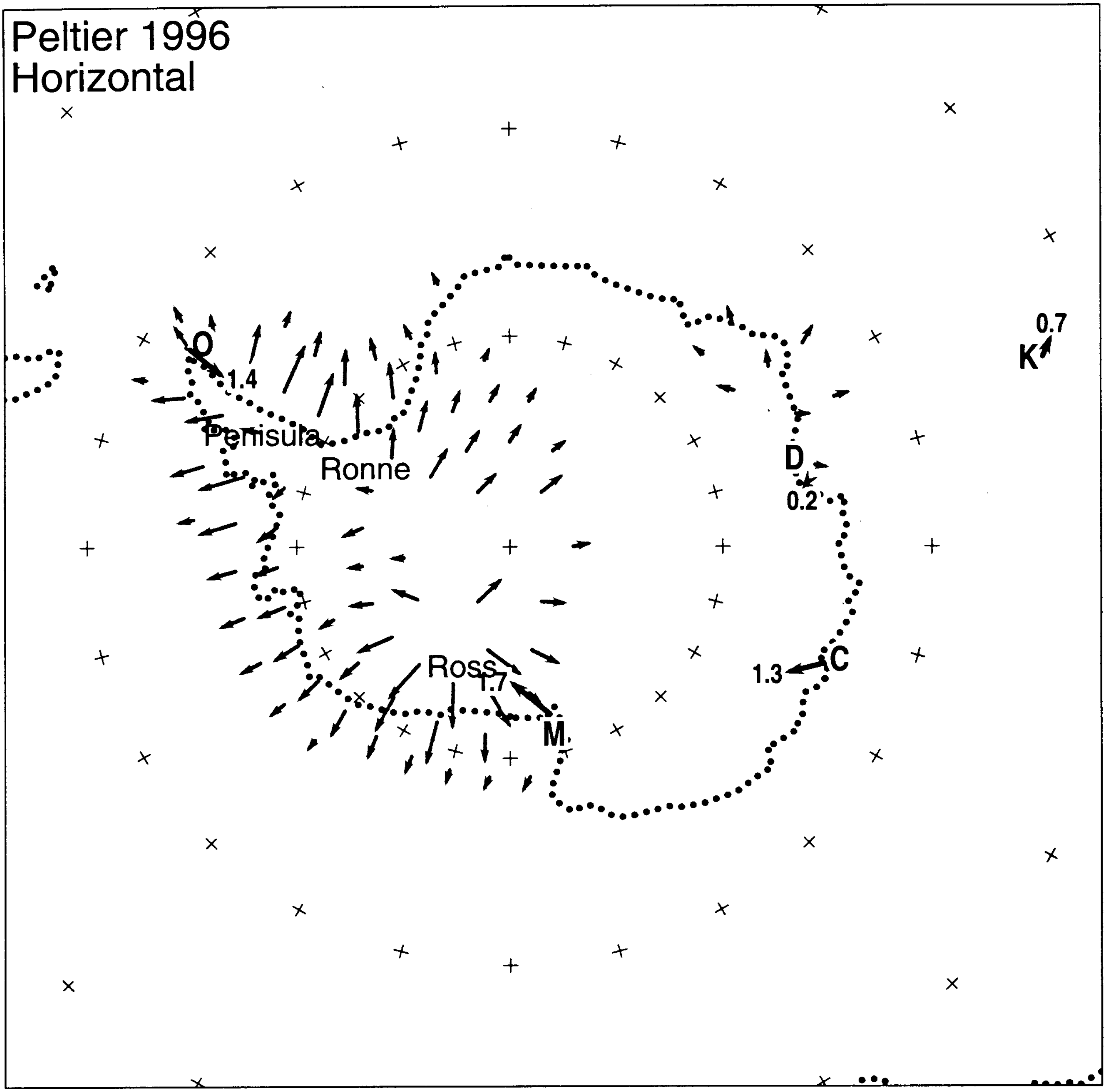

Peltier 1994
Horizontal
NA
0.3
1.6
T
K
0.9
M
0.8
M
0.6
O
1.5
K
0.2
G
0.3
P
0.2
B
0.4
0.8
J
B
0.7
E
0.7
0.3
W
0.9
1.1
P
Z
0.2
G
0.7
C
0.3
0.4
M

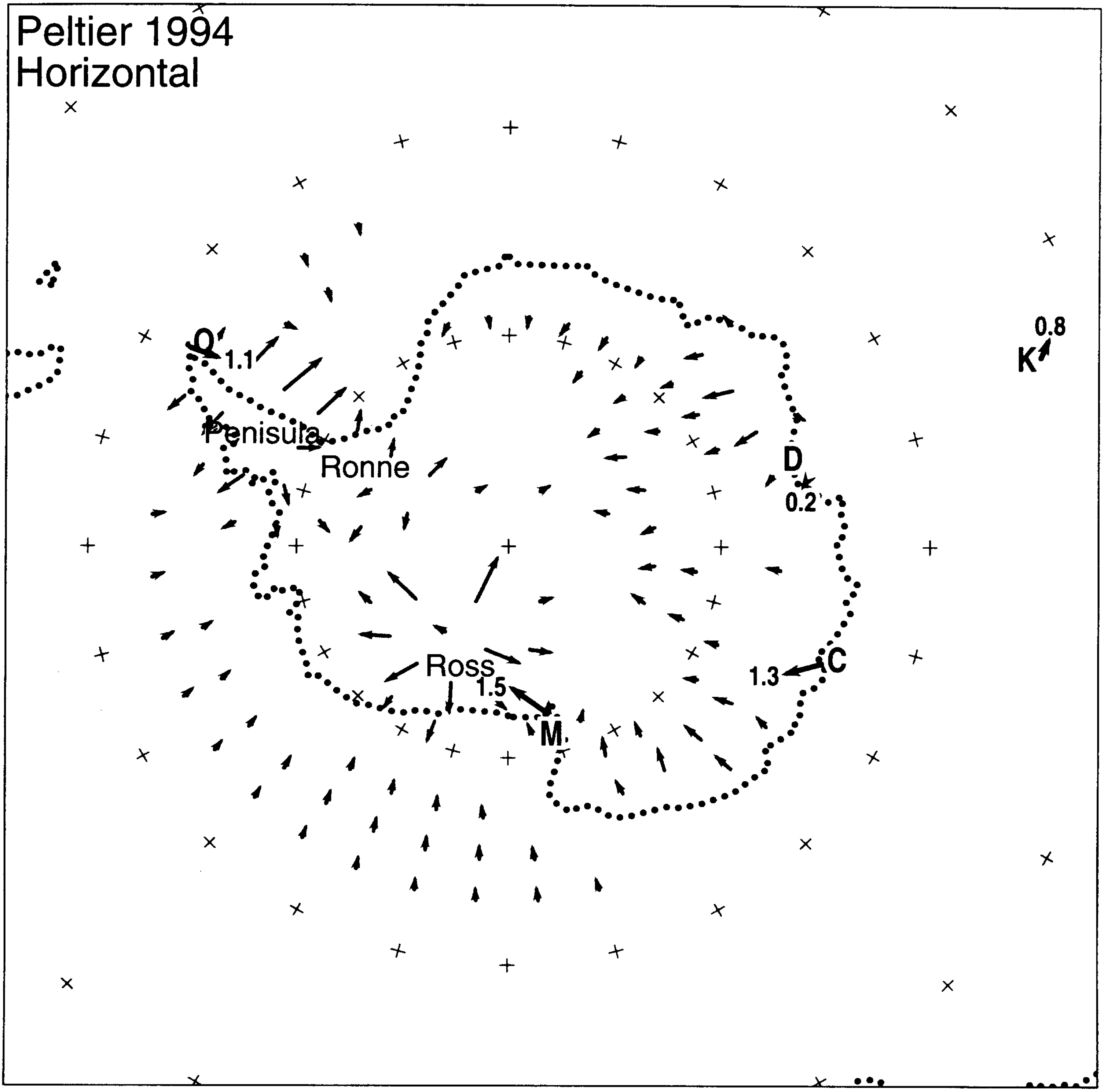


Peltier 1996
Vertical
7
OH
3
D
8
C
4
K
M
0
–5
–2
0
+2
+5
+10
+15
mm/year
down
up
Vertical Rate



Peltier 1994
Vertical
7
OH
3
D
8
C
4
K
M
0
–5
–2
0
+2
+5
+10
+15 mm/year
down
up
Vertical Rate


Peltier 1996
Horizontal
O
1.4
Penisula
Ronne
Ross
1.7
M
D
0.2
C
1.3
K
0.7


Peltier 1994
Horizontal
O
1.1
Penisula
Ronne
Ross
1.5
M
D
0.2
C
1.3
K
0.8

Science Applications

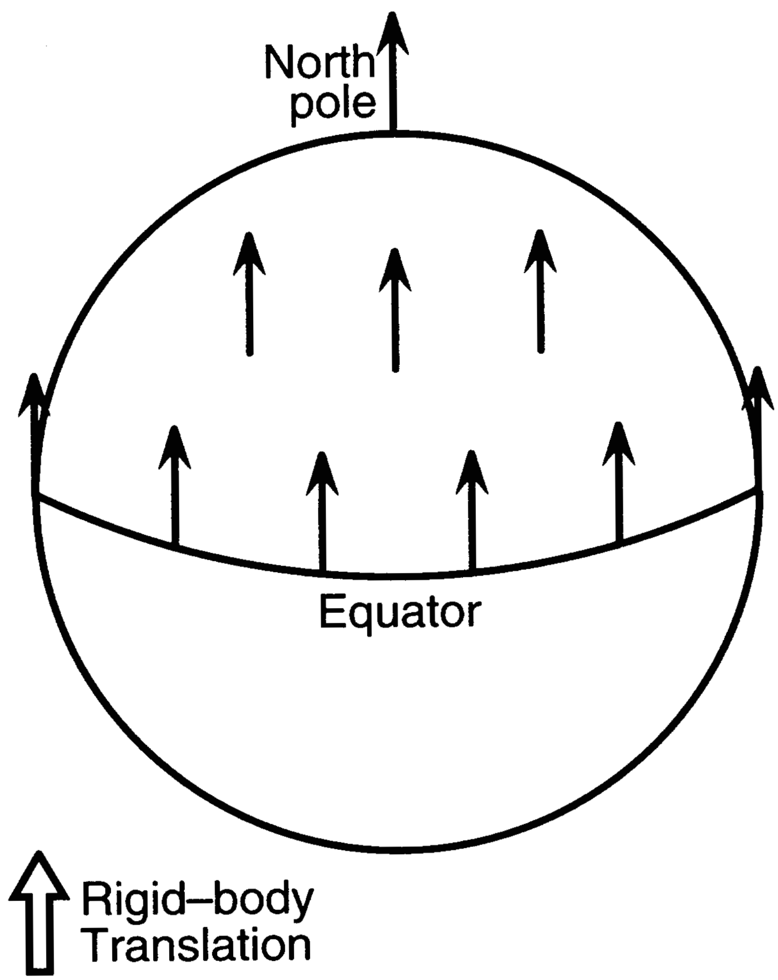
⑤ What is space geodesy bringing to postglacial rebound models?

Horizontal motion
slow motion away from
former ice sheet centers
Algonquin Park 1 mm/year
Onsala 1 mm/year

Vertical motion of continent interiors
Yellowknife rising
at 8 ±2 mm/year
west Laurentide ice sheet
must be thicker

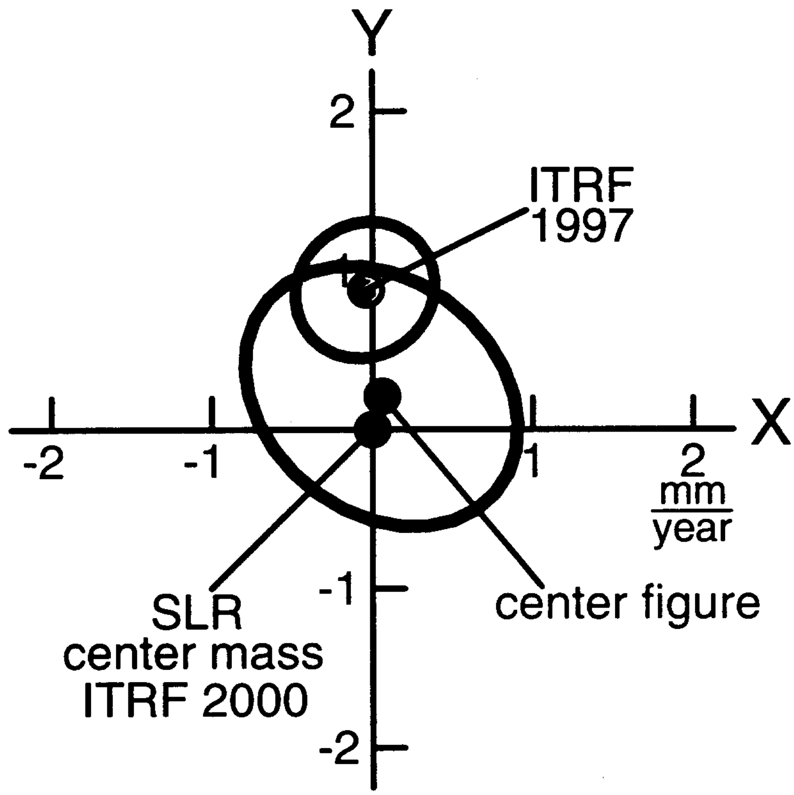
Conclusion
Space geodesy is
bringing new information
to postglacial rebound.

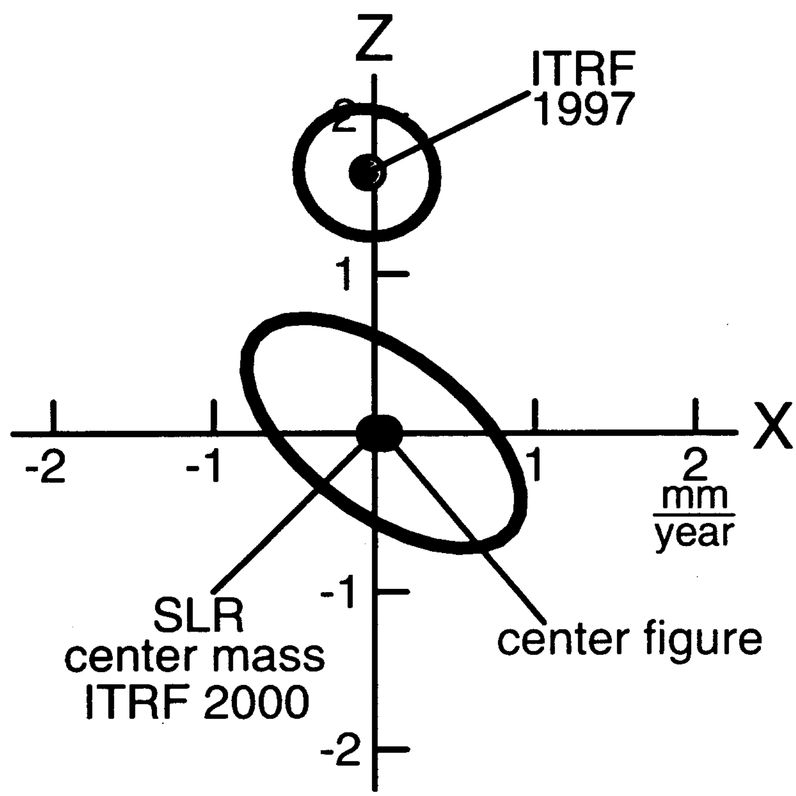
Part 6
Earth Center Motion

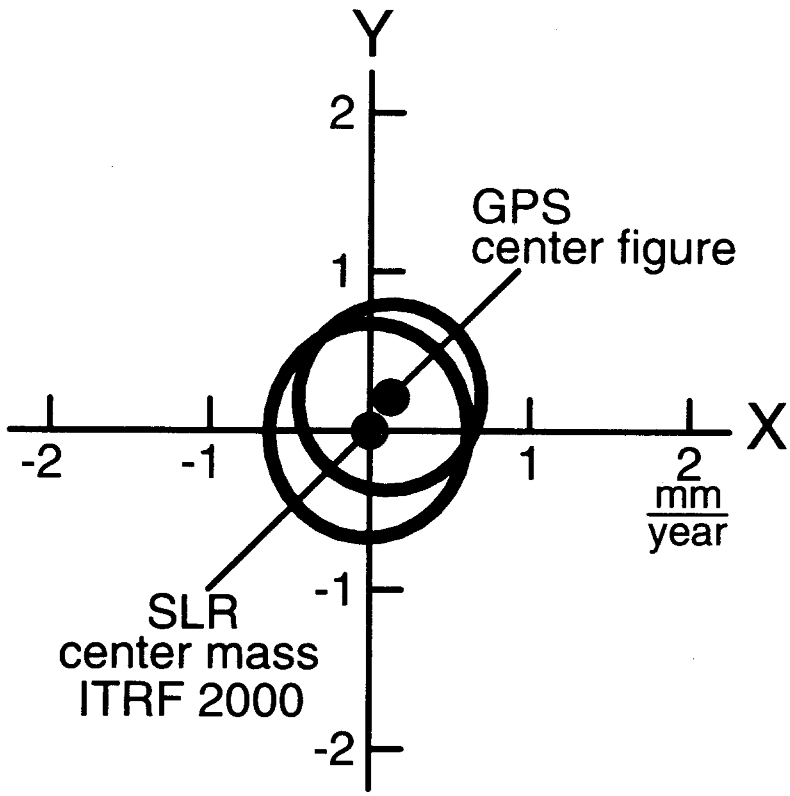

North pole
Equator
Rigid–body Translation

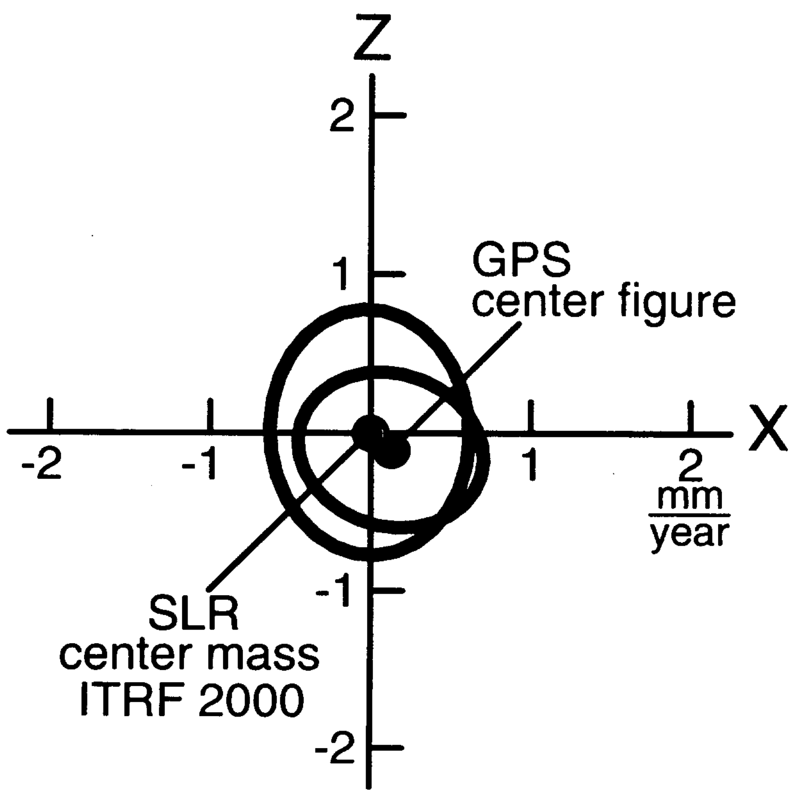
DEFINITION OF REFERENCE FRAME

ITRF 1997	Argus et al.	ASSUMPTION
X		relative plate motions equal those in NUVEL-1A
X		no net rotation of the plates relative to the deep earth interior
X	X	the plates are rigid
X	X	the plate interiors neither rise nor fall
	X	the velocity between the the geocenter and mass center is negligible


Y
2
ITRF
1997
X
-2
-1
1
2
mm
year
-1
SLR
center mass
ITRF 2000
center figure
-2


Z
ITRF
1997
2
1
X
-2
-1
1
2
mm
year
-1
SLR
center mass
ITRF 2000
center figure
-2


Y
2
GPS
center figure
1
X
-2
-1
1
2
mm
year
-1
SLR
center mass
ITRF 2000
-2


Z
2
GPS
center figure
1
X
-2
-1
1
2
mm
year
-1
SLR
center mass
ITRF 2000
-2

SCIENCE APPLICATIONS

⑥ Motion between
GPS center of figure
SLR center of mass
0.3 ±0.5 mm/year

Conclusion
GPS can define
translational velocity.

PART 7
Spin Axis Wander

Defining the Angular Velocity of the Reference Frame:

No Net Rotation vs. Hotspots

22 April 2002 European Geophysical Society

Relative to WHAT?

① 1 plate

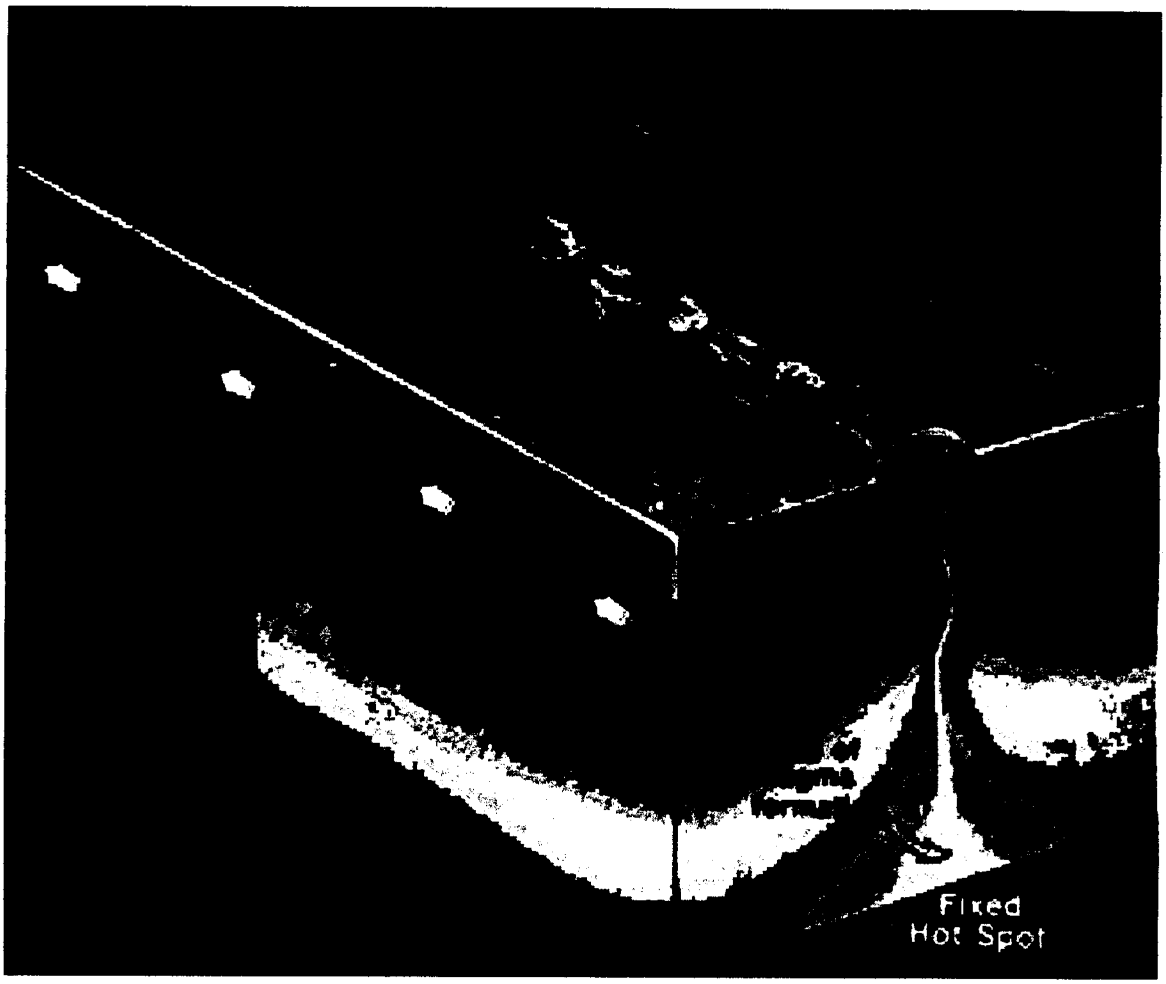
② mean lithosphere
=no net rotation
of the plates

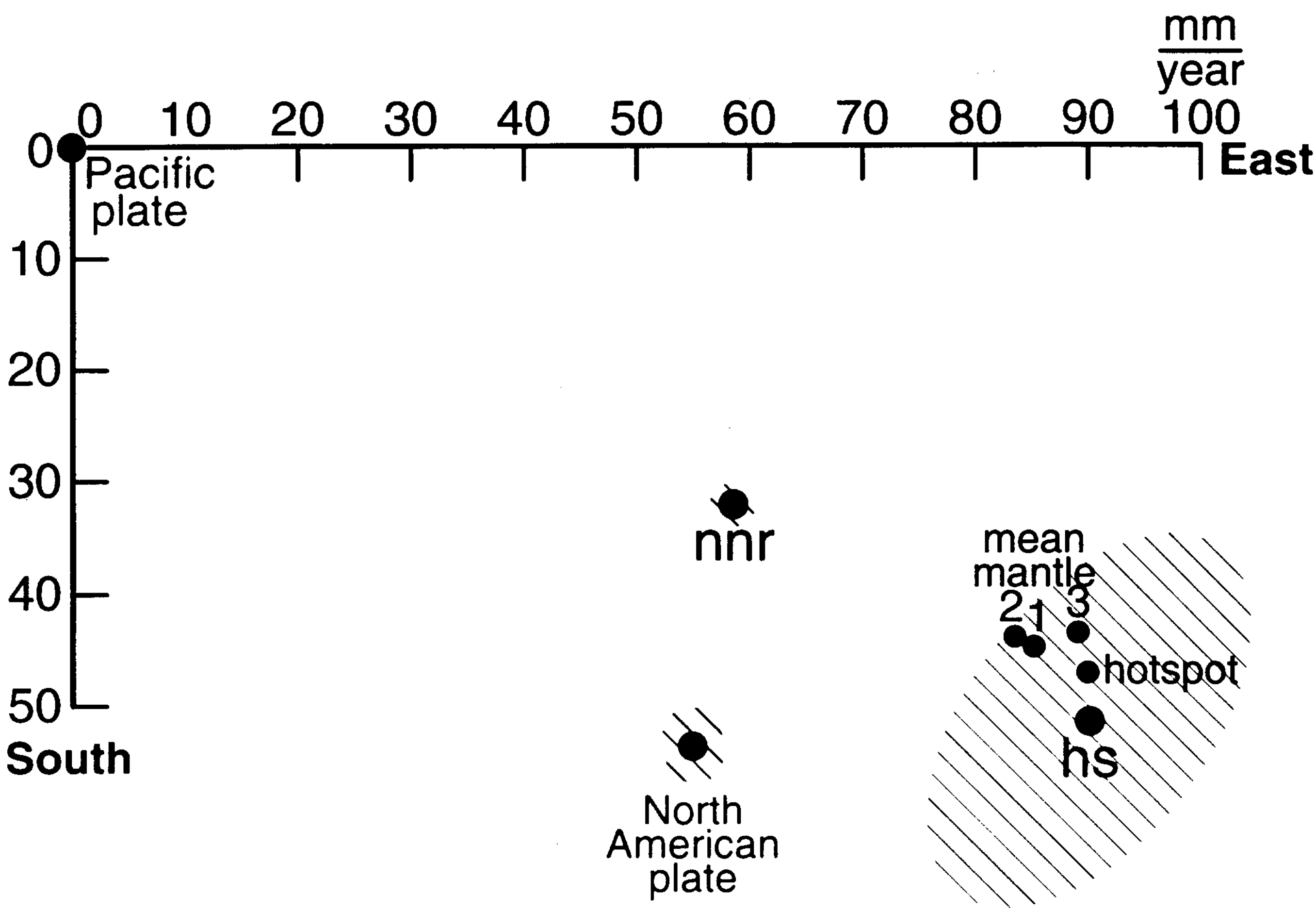
③ hotspots

④ mean mantle
(using a geodynamic model
of mantle convection)

differ

$$48\,\frac{\text{mm}}{\text{year}}$$


Fixed
Hot Spot



mm
year
0
10
20
30
40
50
60
70
80
90
100
East
0
Pacific
plate
10
20
30
40
50
South
nnr
mean
mantle
2
1
3
hotspot
hs
North
American
plate

A Revised Estimate of the Motion Between the Spin Axis and the Mantle

17 April 2002 International Astronomical Union

Polar Motion

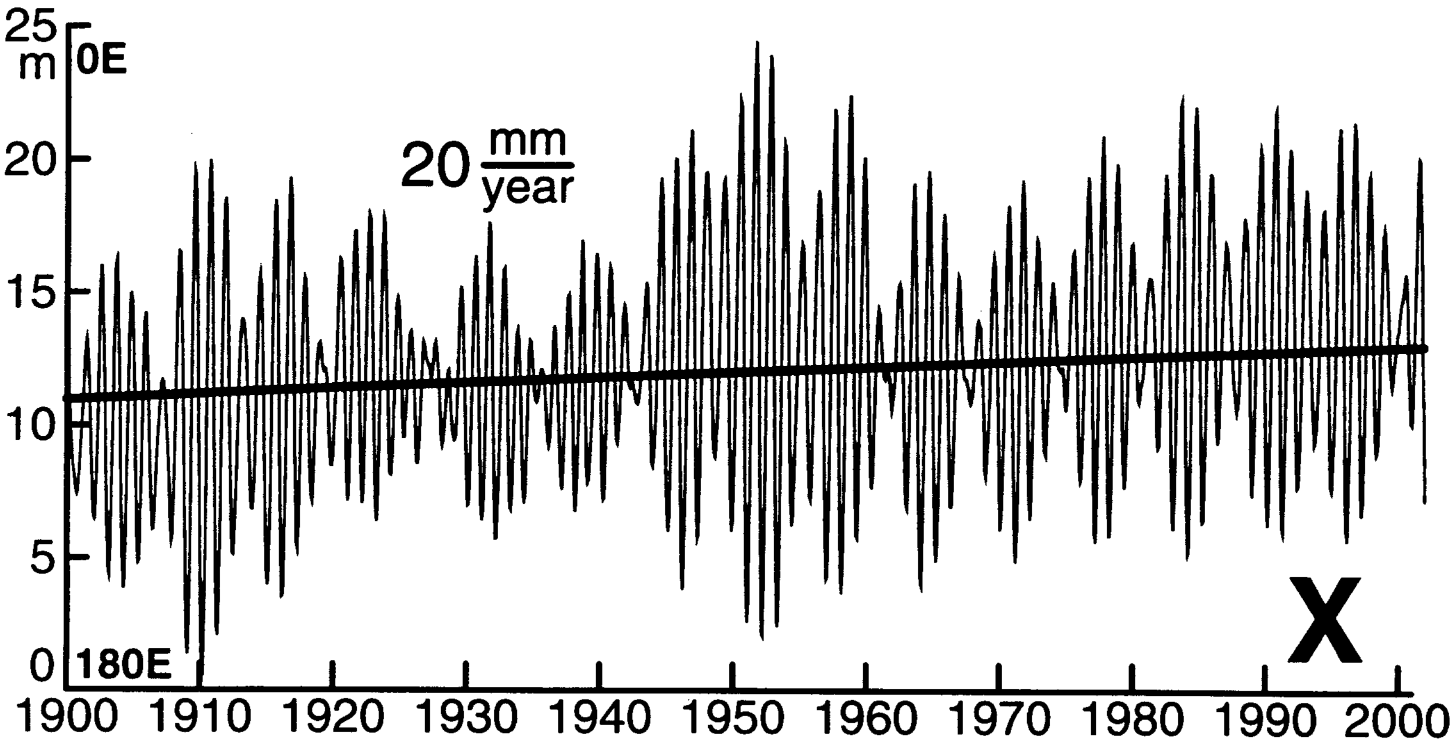
forced annual wobble
3 meter amplitude
1 year period

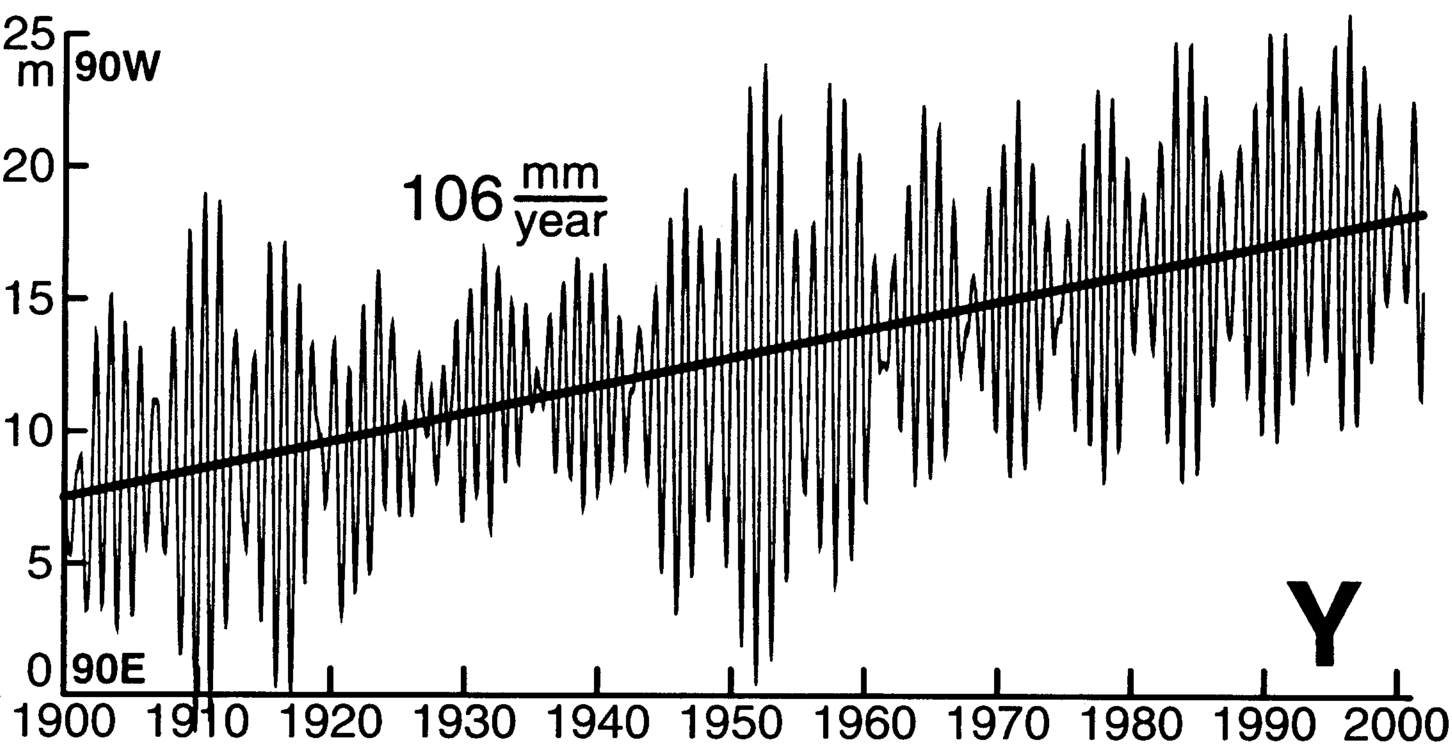
free Chandler wobble
3 to 6 meter amplitude
433 day period

Markowitz wobble
1 meter amplitude
30 year? period

constant velocity
11 meter/100 year
along 75°W meridian

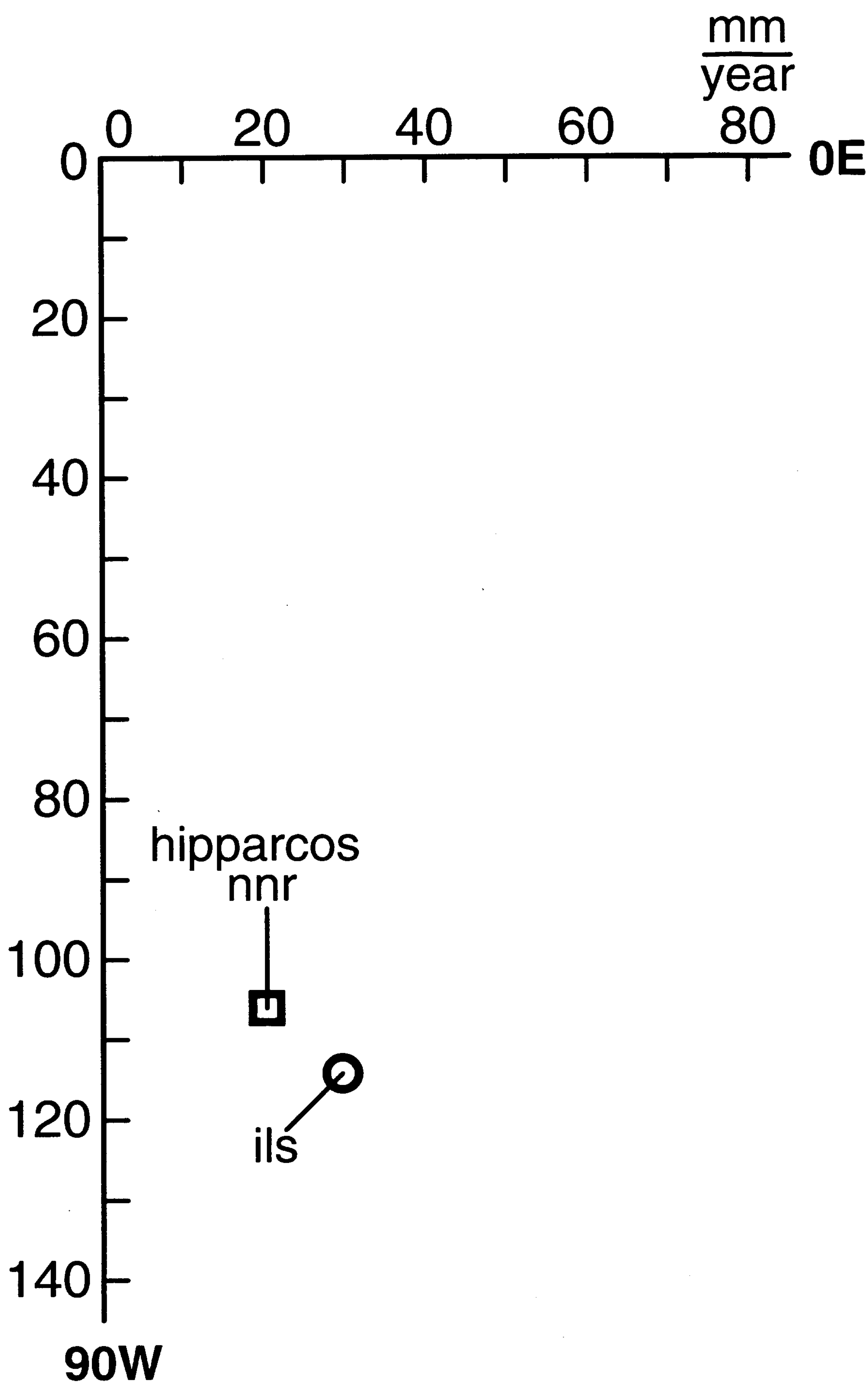
Polar Motion



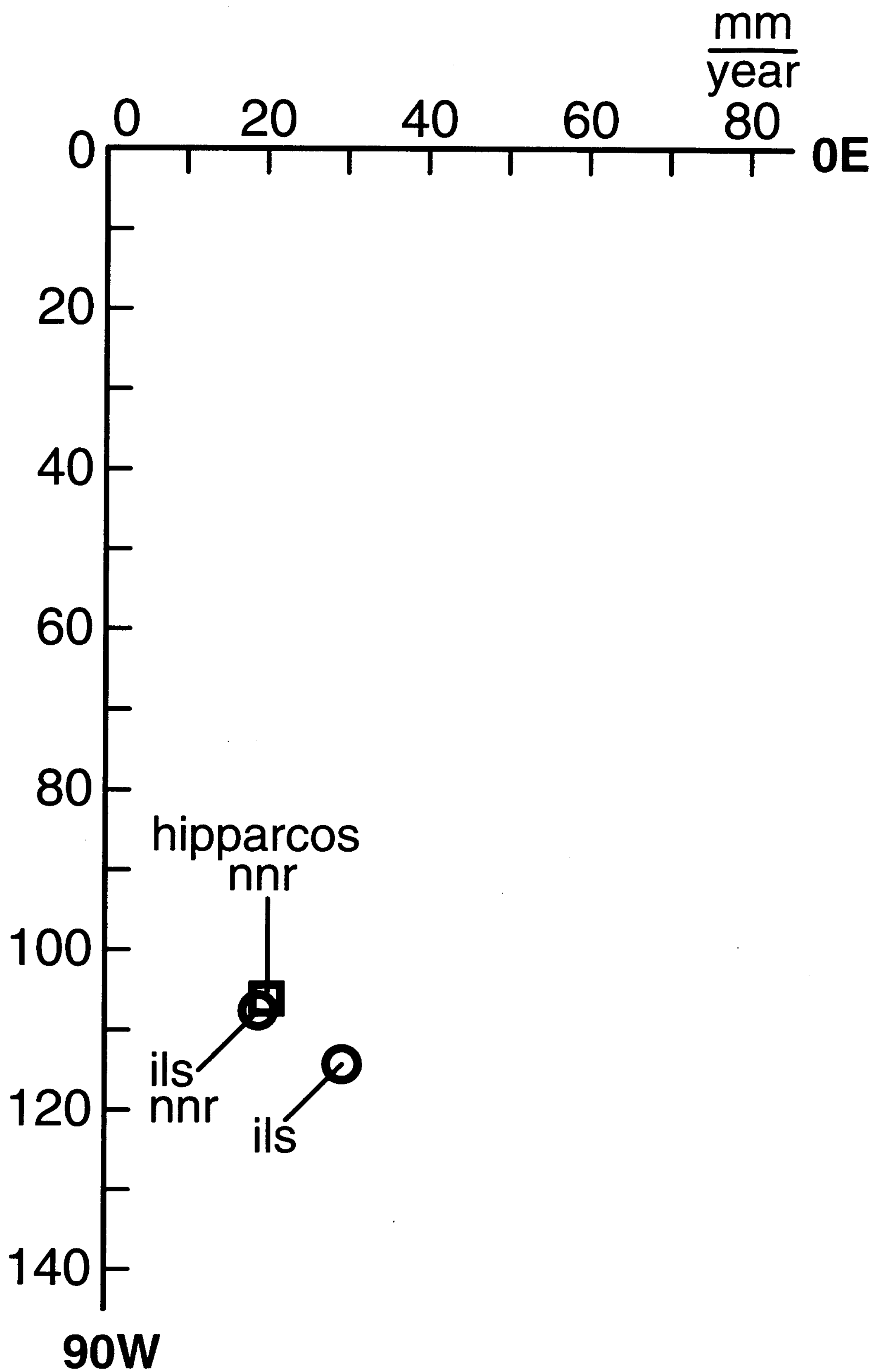


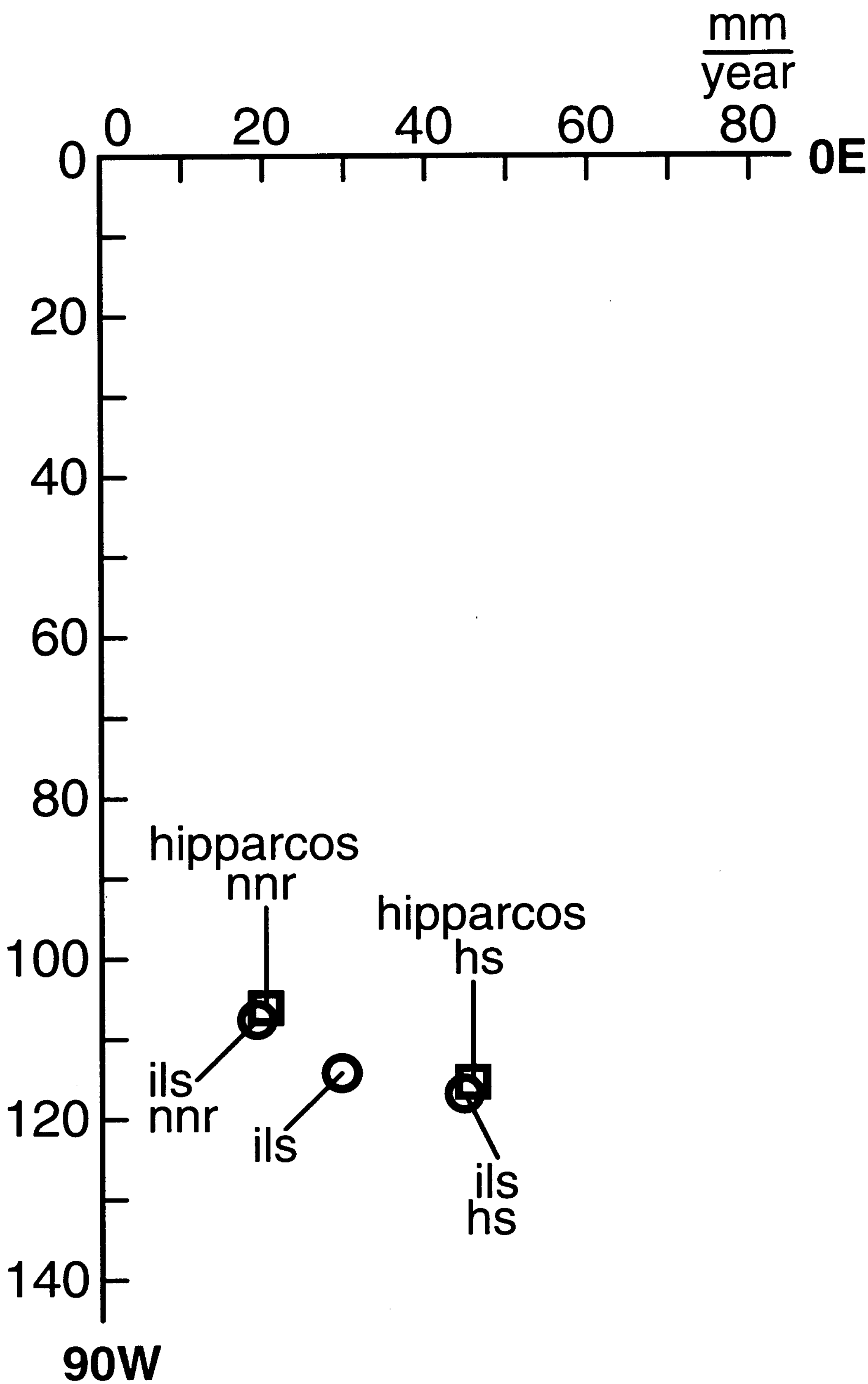
POLE2001

Richard Gross 2002

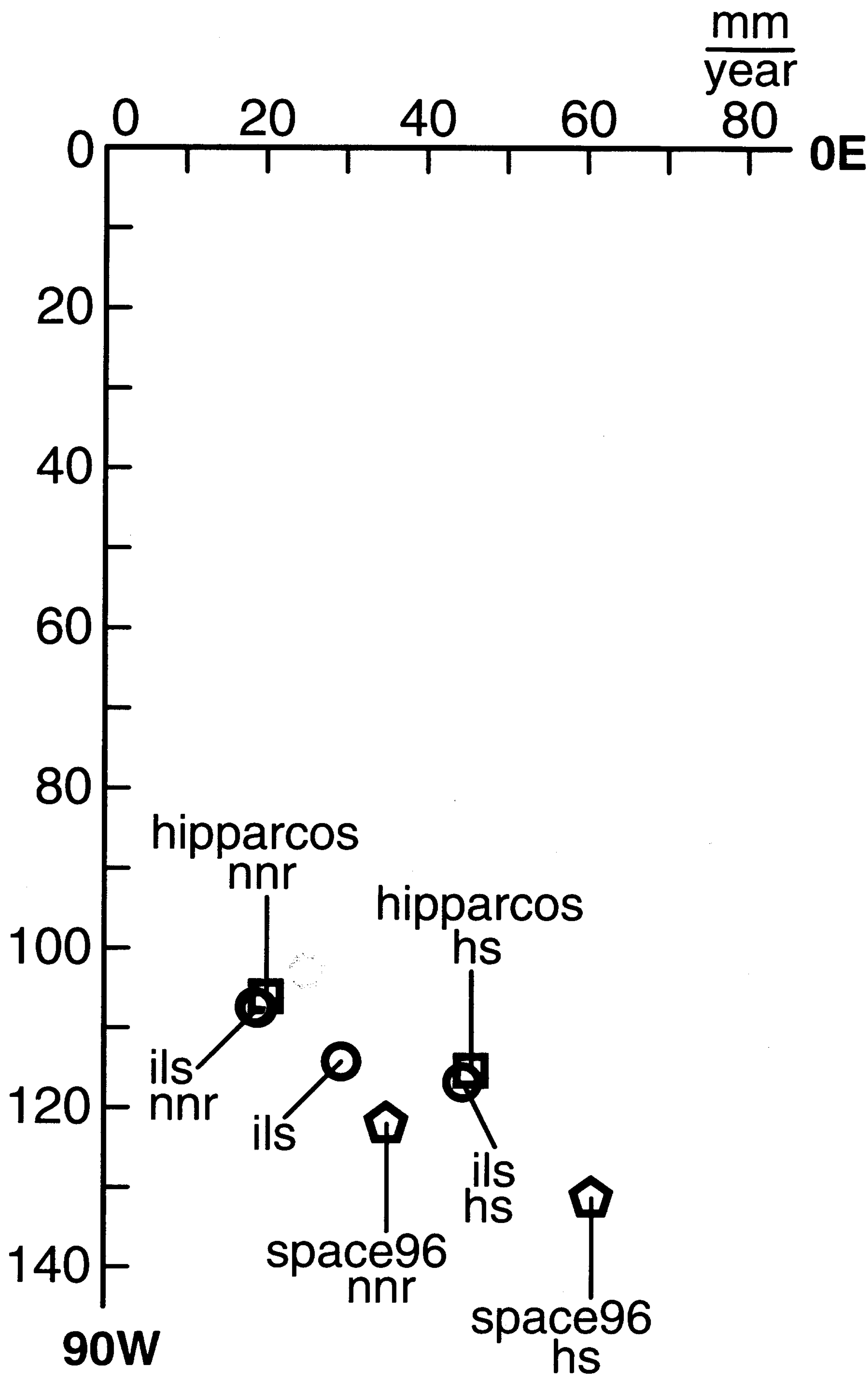


mm/year
0
20
40
60
80
0E
0
20
40
60
80
100
120
140
90W
hipparcos
nnr
ils

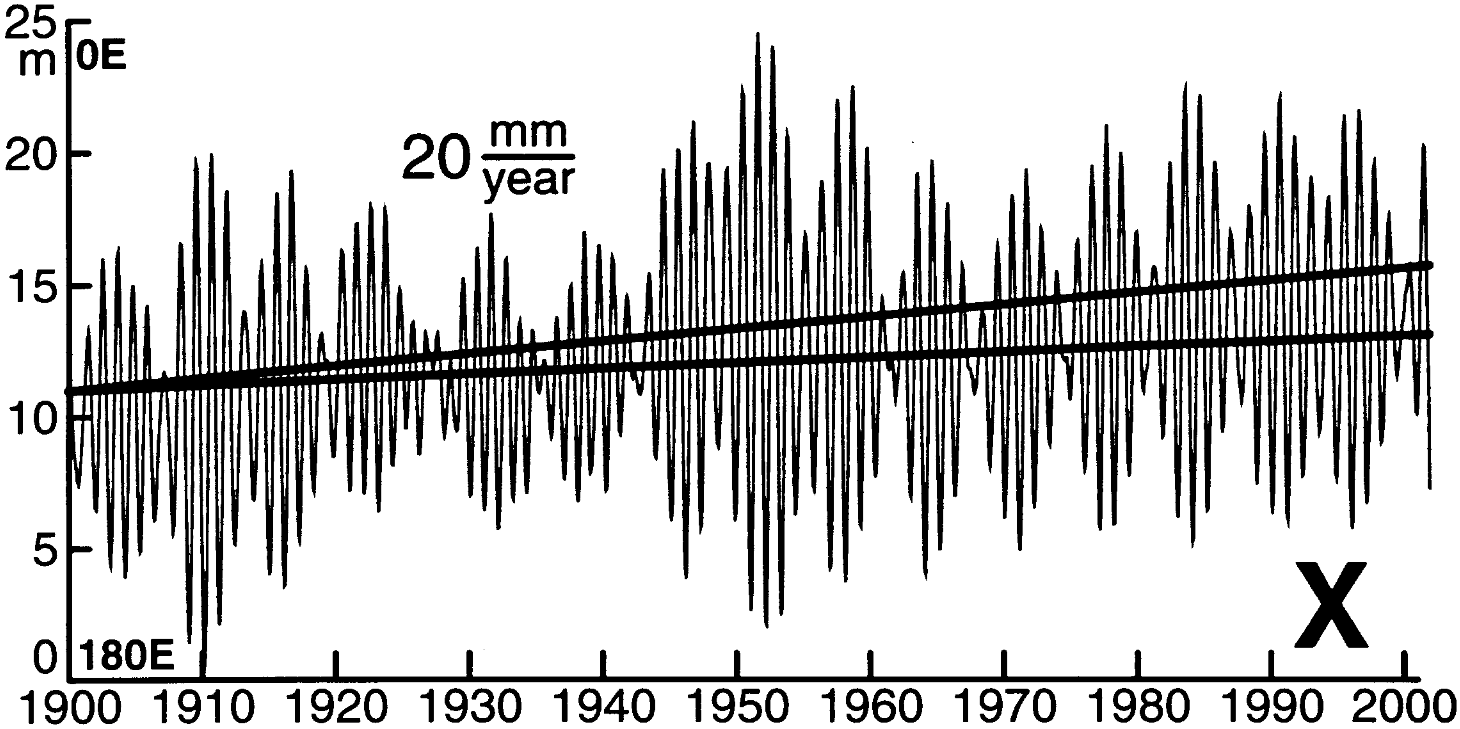

mm/year
0
20
40
60
80
0E
0
20
40
60
80
100
120
140
90W
hipparcos nnr
ils nnr
ils

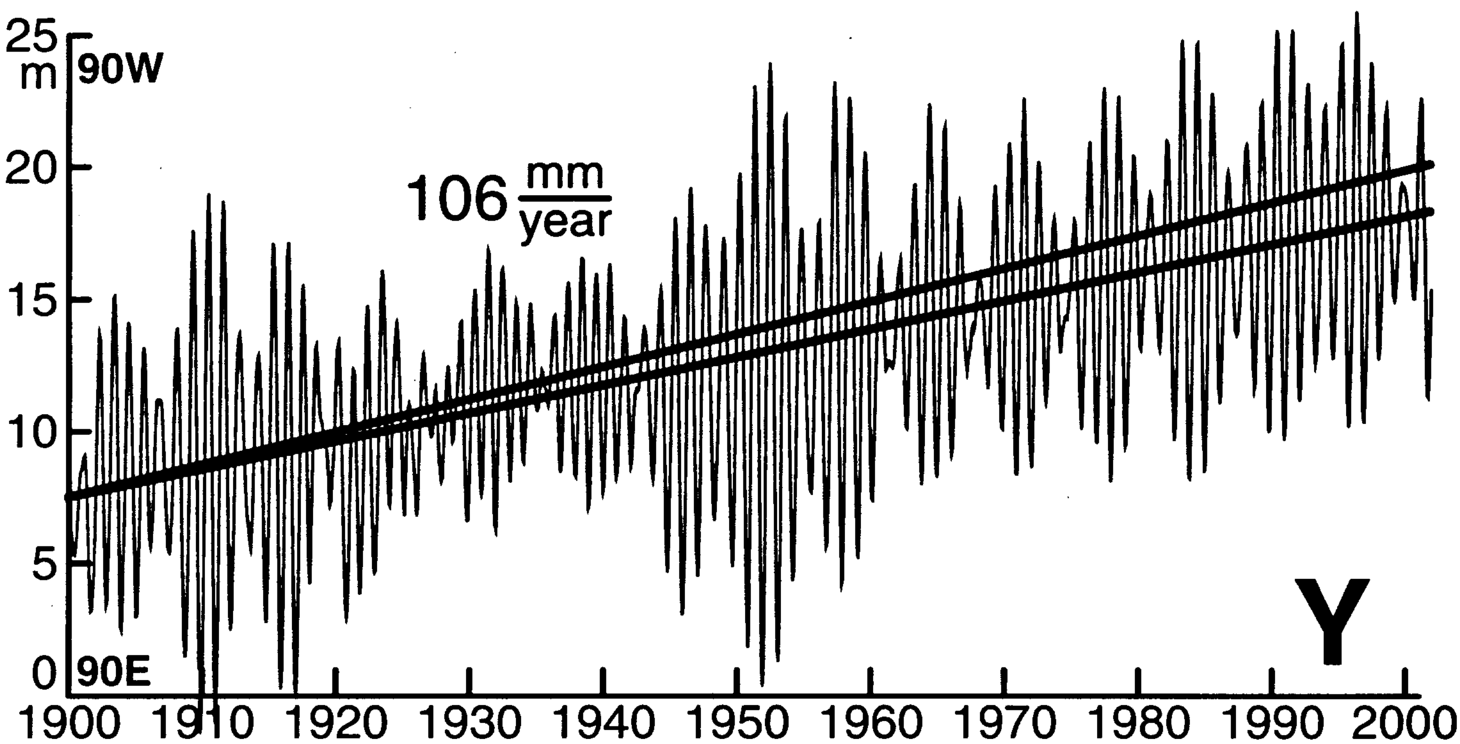


mm/year
0
20
40
60
80
0E
0
20
40
60
80
100
120
140
90W
hipparcos
nnr
hipparcos
hs
ils
nnr
ils
ils
hs


mm
year
0
20
40
60
80
0
0E
20
40
60
80
100
120
140
90W
hipparcos
nnr
hipparcos
hs
ils
nnr
ils
ils
hs
space96
nnr
space96
hs

Polar Motion





POLE2001

Richard Gross 2002

$$123 \frac{\text{mm}}{\text{year}}$$

toward 69°W

differ

$27 \frac{\text{mm}}{\text{year}}$ toward 20°W

revised input to
postglacial rebound model
of Peltier [1996]