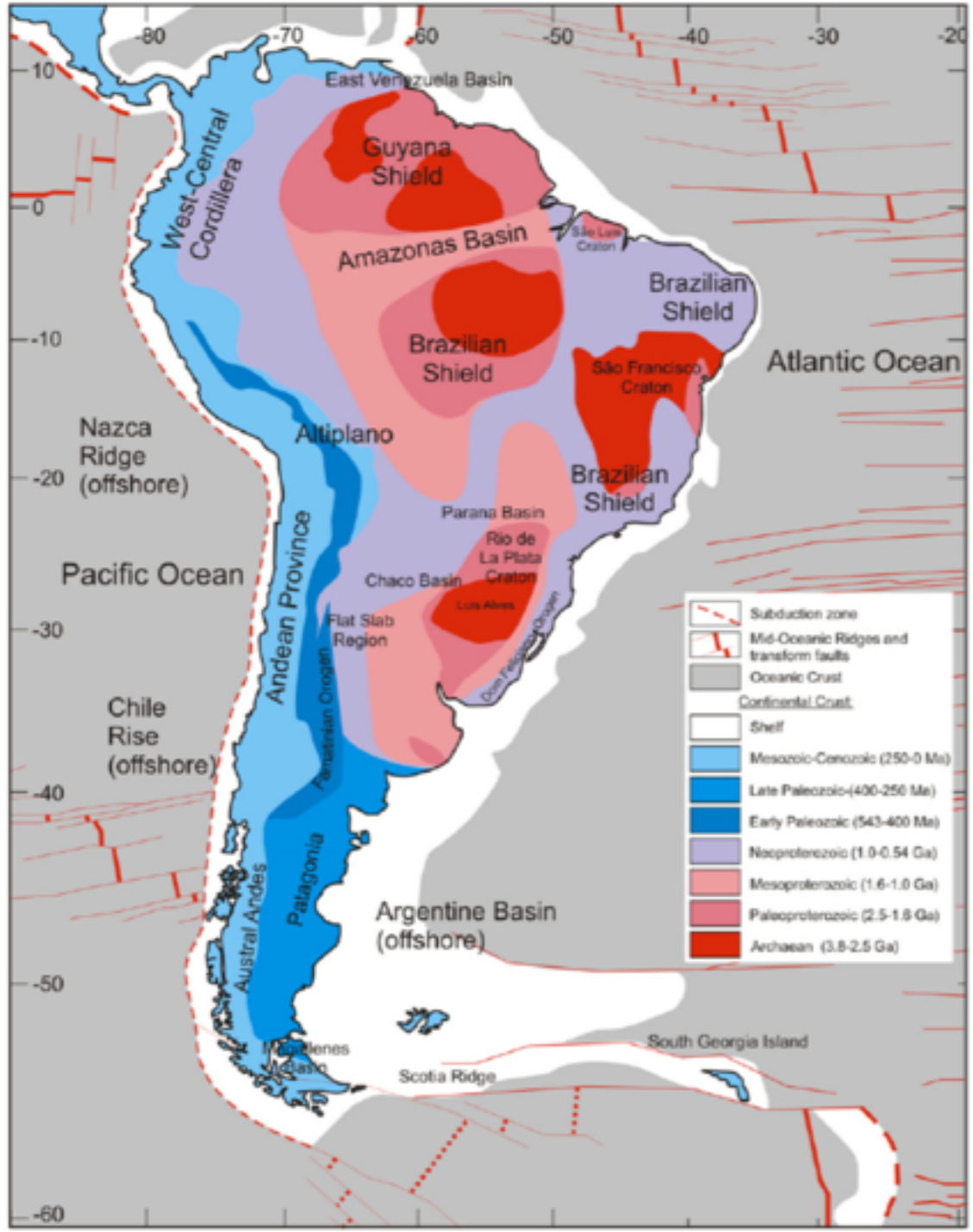
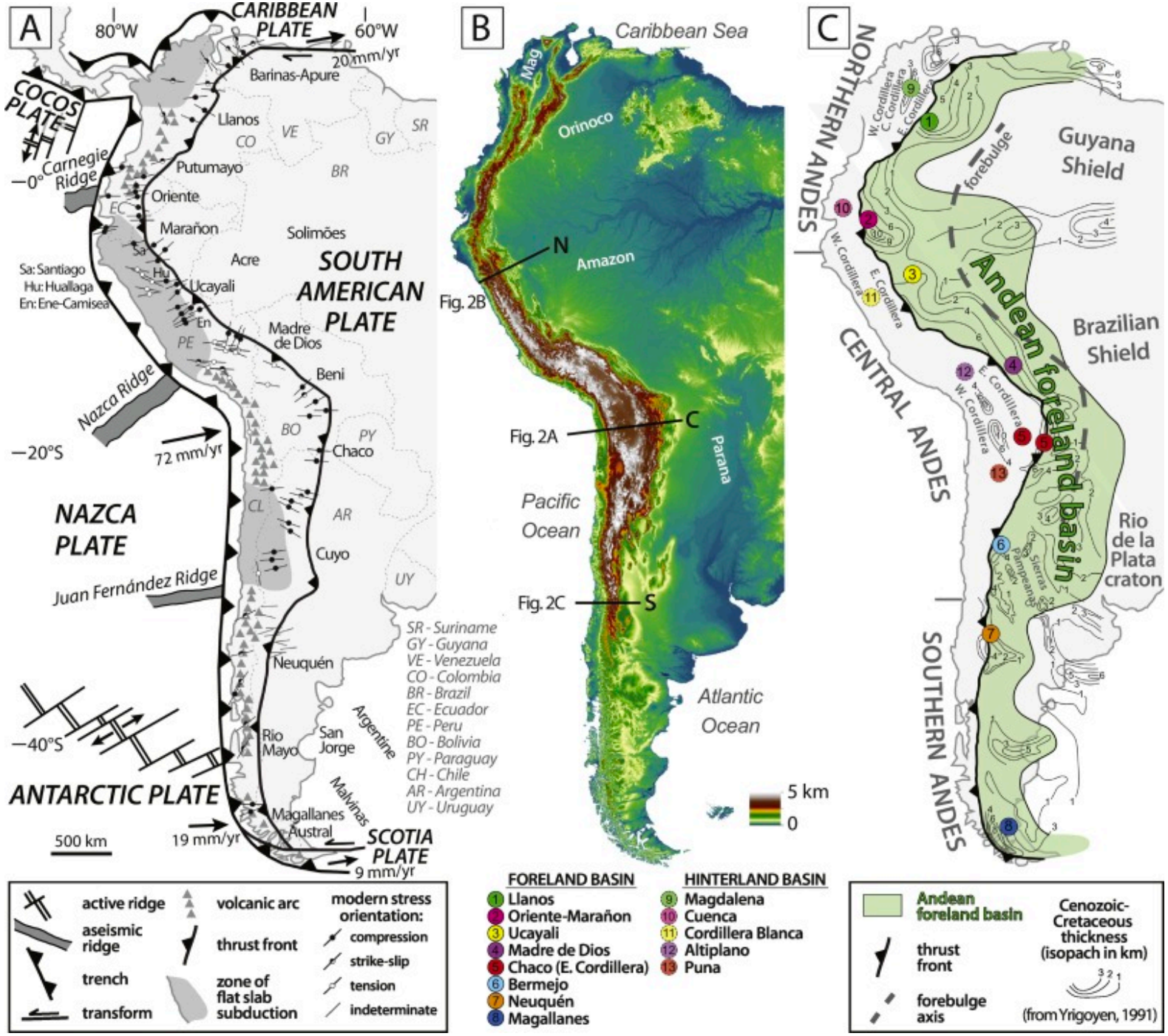
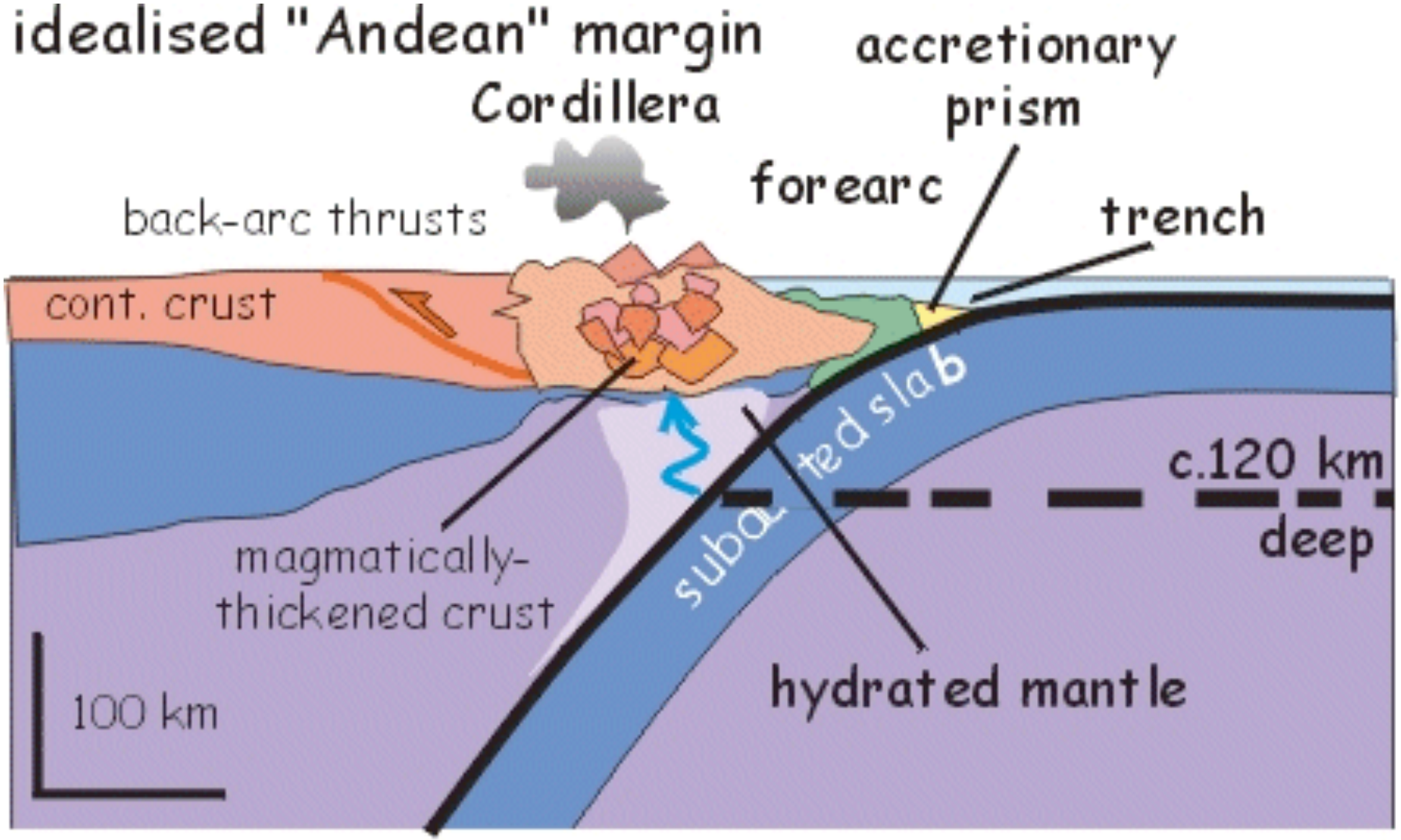
Andes

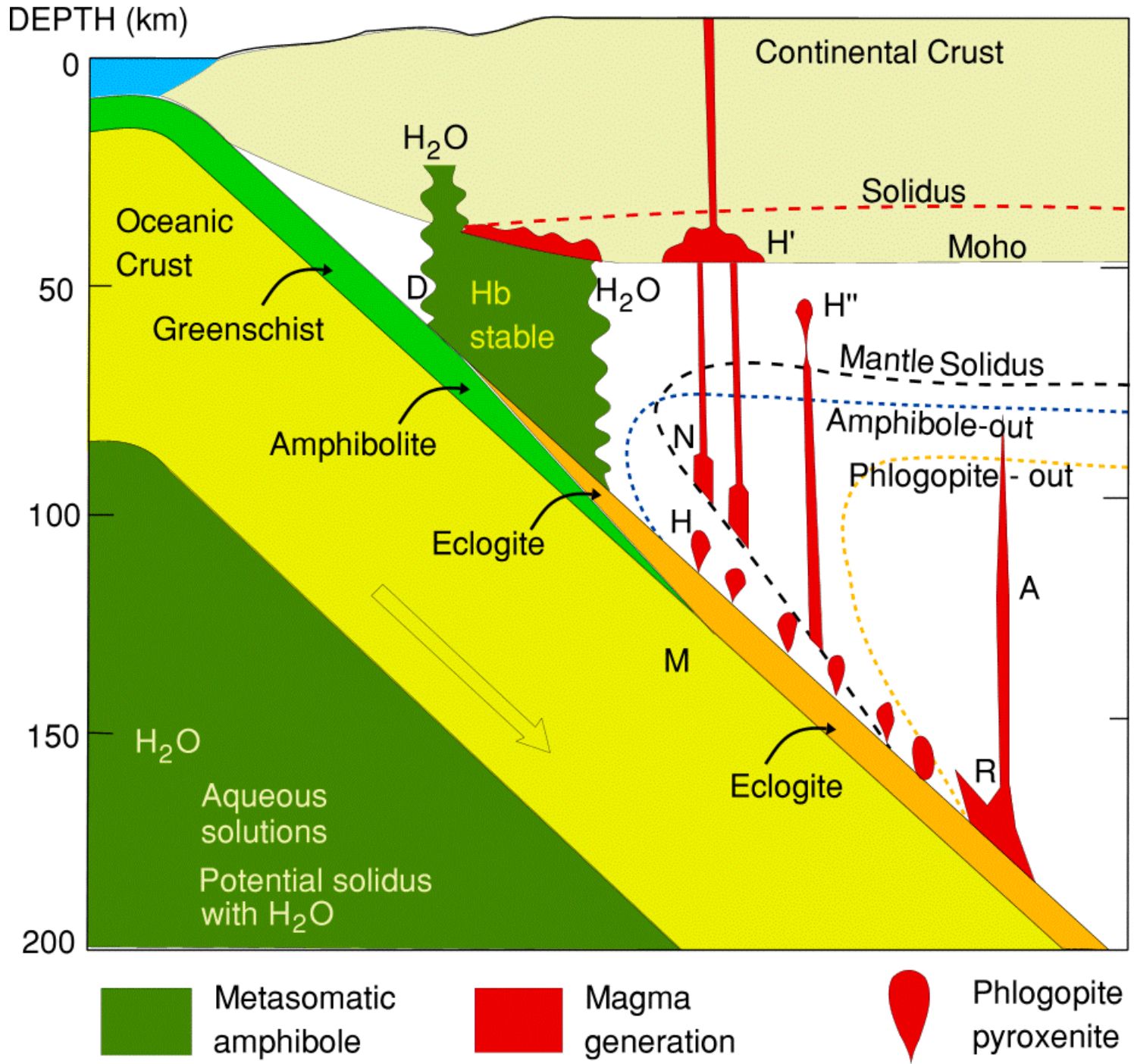

-80
-70
-60
-50
-40
-30
-20
10
0
-10
-20
-30
-40
-50
-60
East Venezuela Basin
Guyana Shield
West-Central Cordillera
Amazonas Basin
São Luis Craton
Brazilian Shield
Brazilian Shield
São Francisco Craton
Atlantic Ocean
Nazca Ridge (offshore)
Altiplano
Brazilian Shield
Parana Basin
Rio de La Plata Craton
Pacific Ocean
Chaco Basin
Luis Alves
Andean Province
Flat Slab Region
Famatinian Orogen
Dom Feliciano Orogen
Chile Rise (offshore)
Patagonia
Austral Andes
Argentine Basin (offshore)
Scotia Ridge
South Georgia Island
Subduction zone
Mid-Oceanic Ridges and transform faults
Oceanic Crust
Continental Crust
Shelf
Mesozoic-Cenozoic (250-0 Ma)
Late Paleozoic-(400-250 Ma)
Early Paleozoic (543-400 Ma)
Neoproterozoic (1.0-0.54 Ga)
Mesoproterozoic (1.6-1.0 Ga)
Paleoproterozoic (2.5-1.8 Ga)
Archaean (3.8-2.5 Ga)

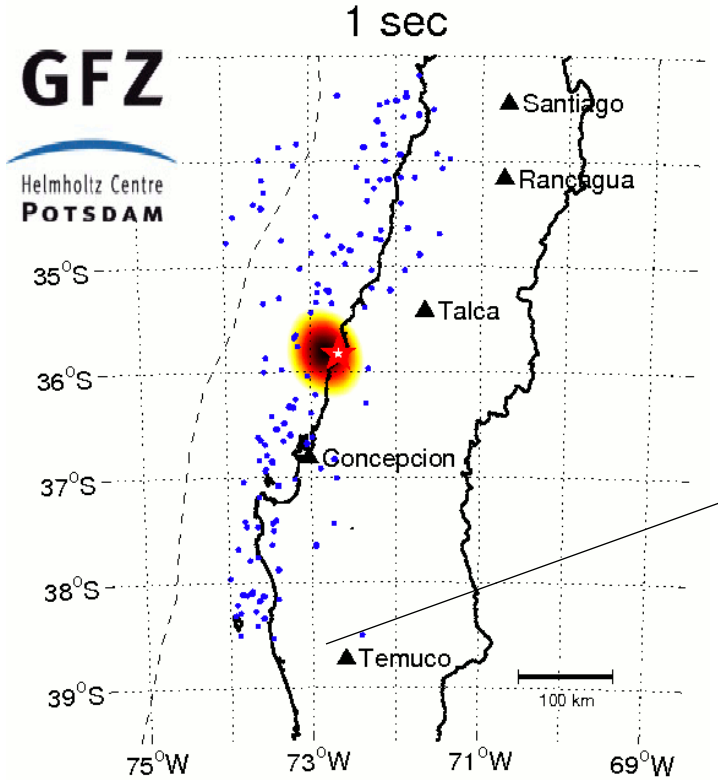

25
24
west centra
14
Rivera
Rivera-
Cocos
Caribbean (CA)
Panamá
23
19
67
Cocos
Galápagos
Andes du Nord
Amérique du Sud
40
32
Nazca
Altiplano
26
OCÉAN PACIFIQUE
51
83
53
Convergent Plate Boundary
Divergent PLate Boundary
Transform PLate Boundary
Subduction Zone Boundary
Speed W.R.T. Africa (mm/yr)


A
80°W
CARIBBEAN PLATE
60°W
20 mm/yr
Barinas-Apure
COCOS PLATE
Carnegie Ridge
0°
Llanos
CO
VE
GY
SR
Putumayo
BR
Oriente
EC
Marañon
Solimões
Sa
Hu
Acre
SOUTH AMERICAN PLATE
Sa: Santiago
Hu: Huallaga
En: Ene-Camisea
Ucayali
En
Madre de Dios
PE
Beni
Nazca Ridge
BO
PY
Chaco
20°S
72 mm/yr
NAZCA PLATE
CL
AR
Cuyo
Juan Fernández Ridge
UY
SR - Suriname
GY - Guyana
VE - Venezuela
CO - Colombia
BR - Brazil
EC - Ecuador
PE - Peru
BO - Bolivia
PY - Paraguay
CH - Chile
AR - Argentina
UY - Uruguay
Neuquén
40°S
Rio Mayo
San Jorge
Argentine
Malvinas
ANTARCTIC PLATE
Magallanes Austral
19 mm/yr
SCOTIA PLATE
9 mm/yr
500 km
active ridge
aseismic ridge
trench
transform
volcanic arc
thrust front
zone of flat slab subduction
modern stress orientation:
compression
strike-slip
tension
indeterminate
B
Caribbean Sea
Mag
Orinoco
N
Amazon
Fig. 2B
C
Fig. 2A
Parana
Pacific Ocean
Fig. 2C
S
Atlantic Ocean
5 km
0
FORELAND BASIN
1 Llanos
2 Oriente-Marañon
3 Ucayali
4 Madre de Dios
5 Chaco (E. Cordillera)
6 Bermejo
7 Neuquén
8 Magallanes
HINTERLAND BASIN
9 Magdalena
10 Cuenca
11 Cordillera Blanca
12 Altiplano
13 Puna
C
NORTHERN ANDES
W. Cordillera
C. Cordillera
E. Cordillera
forebulge
Guyana Shield
Andean foreland basin
Brazilian Shield
CENTRAL ANDES
Sierras Pampeanas
Rio de la Plata craton
SOUTHERN ANDES
Andean foreland basin
thrust front
forebulge axis
Cenozoic-Cretaceous thickness (isopach in km)
(from Yrigoyen, 1991)

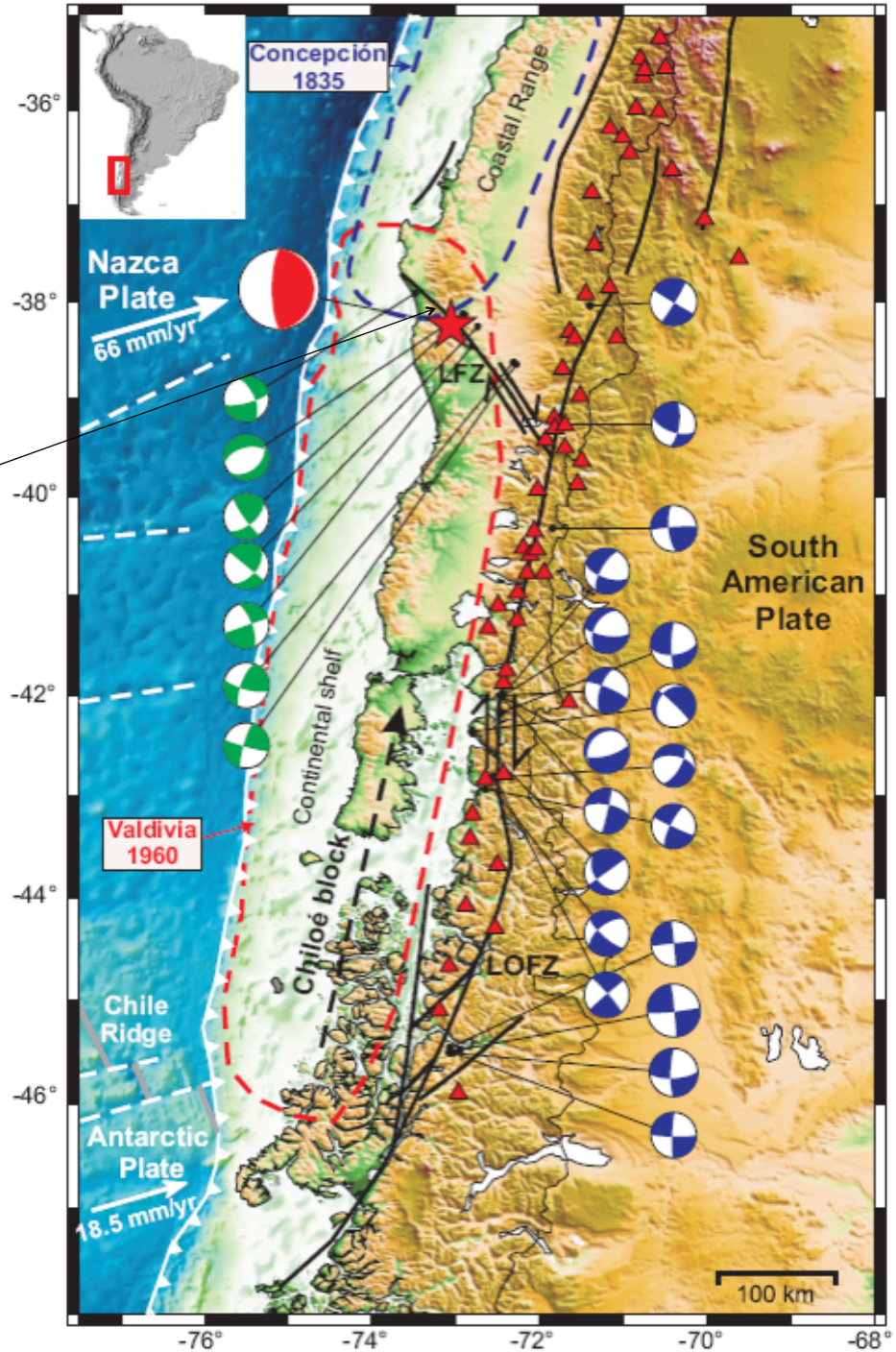


subduction of oceanic lithosphere under continental lithosphere


DEPTH (km)
0
50
100
150
200
Continental Crust
H_2O
Solidus
Moho
H'
Oceanic
Crust
Greenschist
D
Hb
stable
H_2O
H"
Mantle Solidus
Amphibole-out
Phlogopite - out
N
H
Amphibolite
Eclogite
A
M
H_2O
Aqueous
solutions
Potential solidus
with H_2O
Eclogite
R
Metasomatic
amphibole
Magma
generation
Phlogopite
pyroxenite

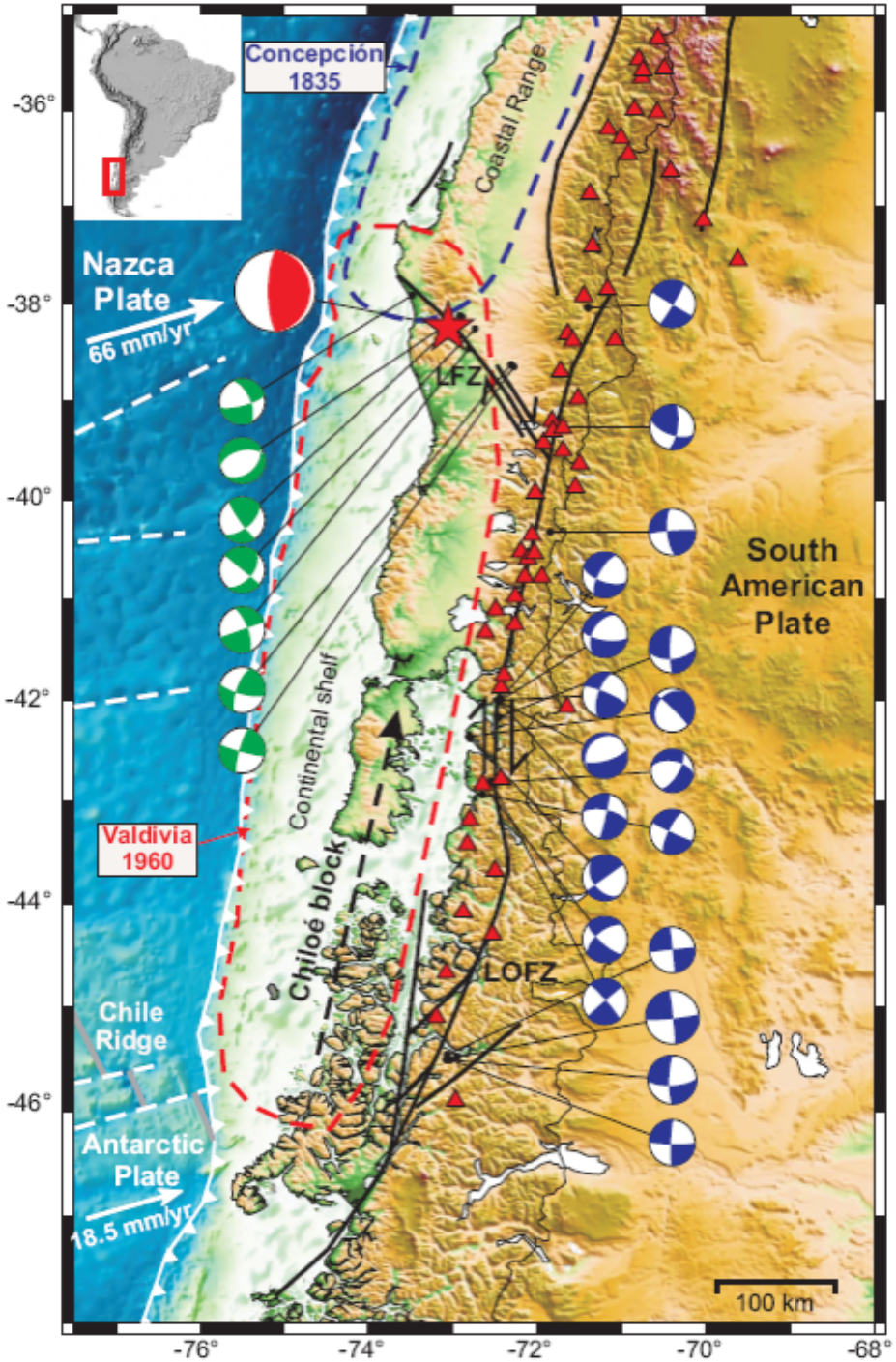


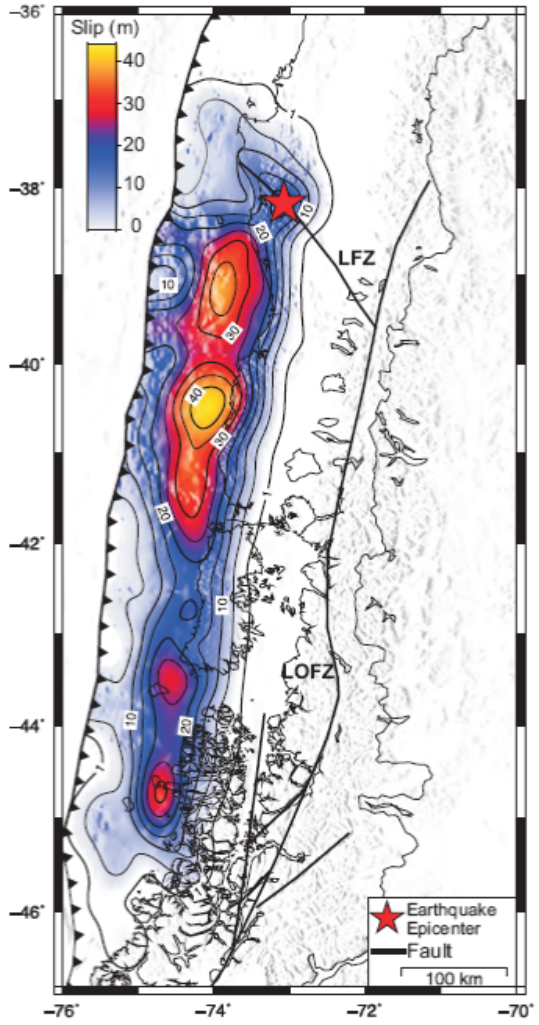
Chile earthquake (2010, Mw=8.8)

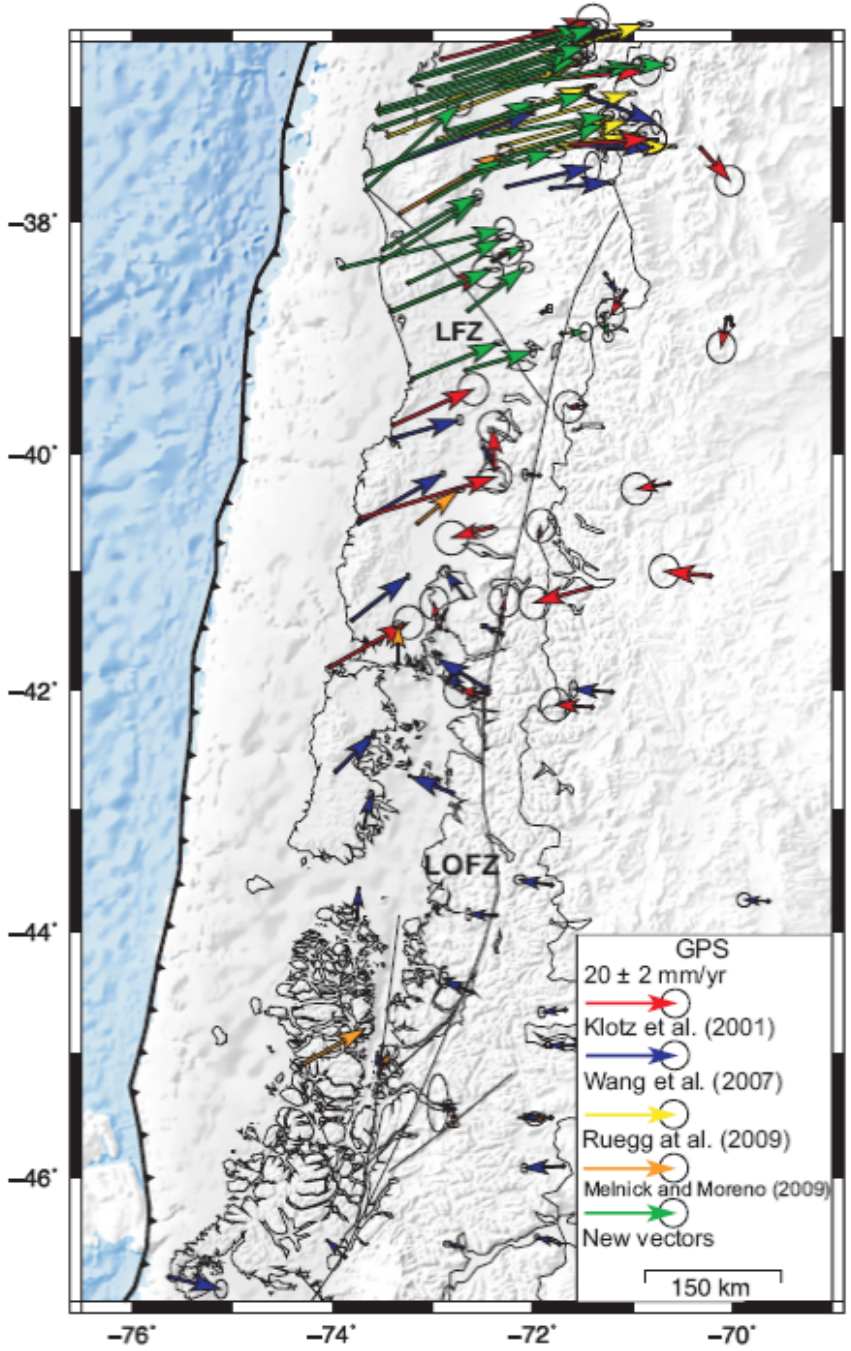


Valdivia earthquake (1960)

Slip distribution



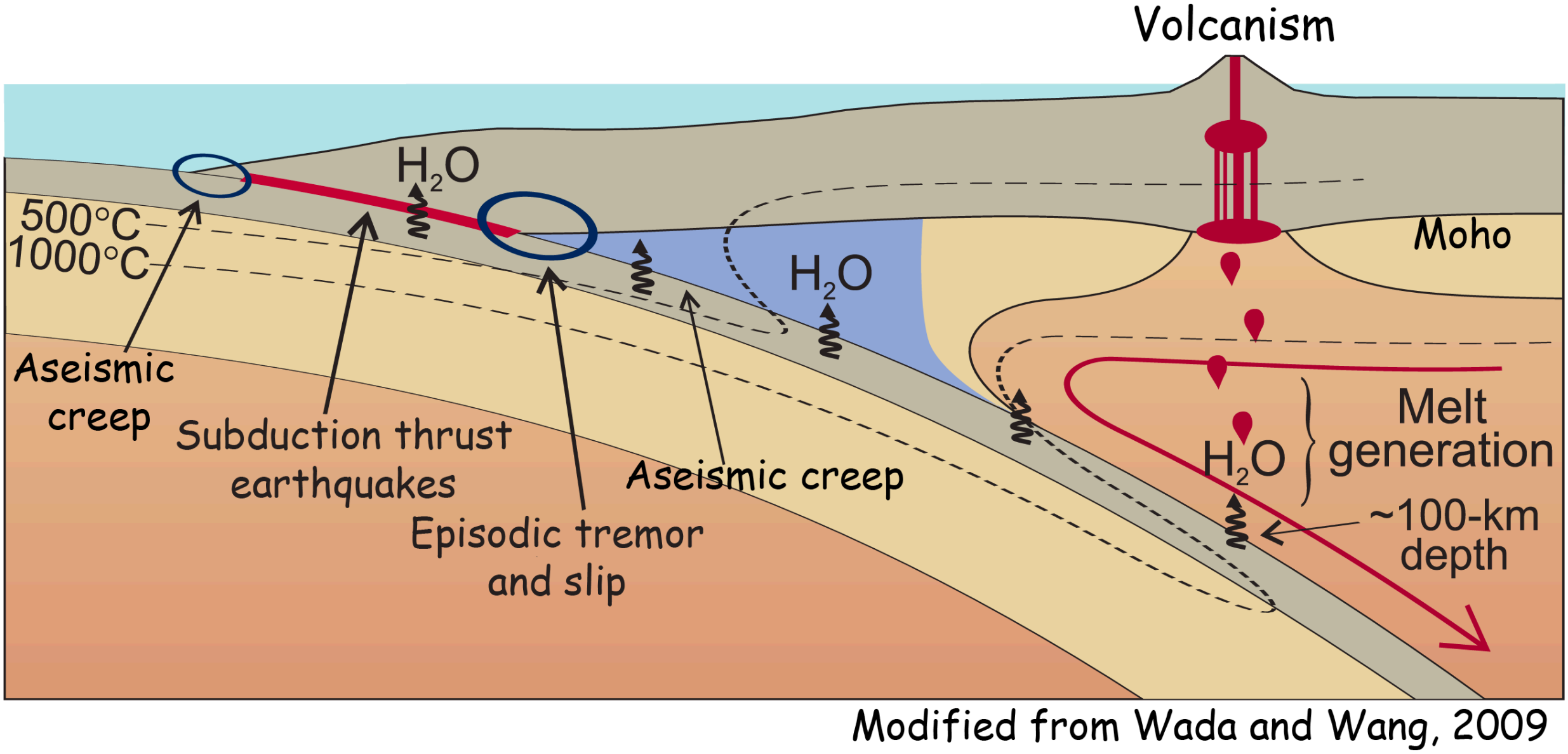




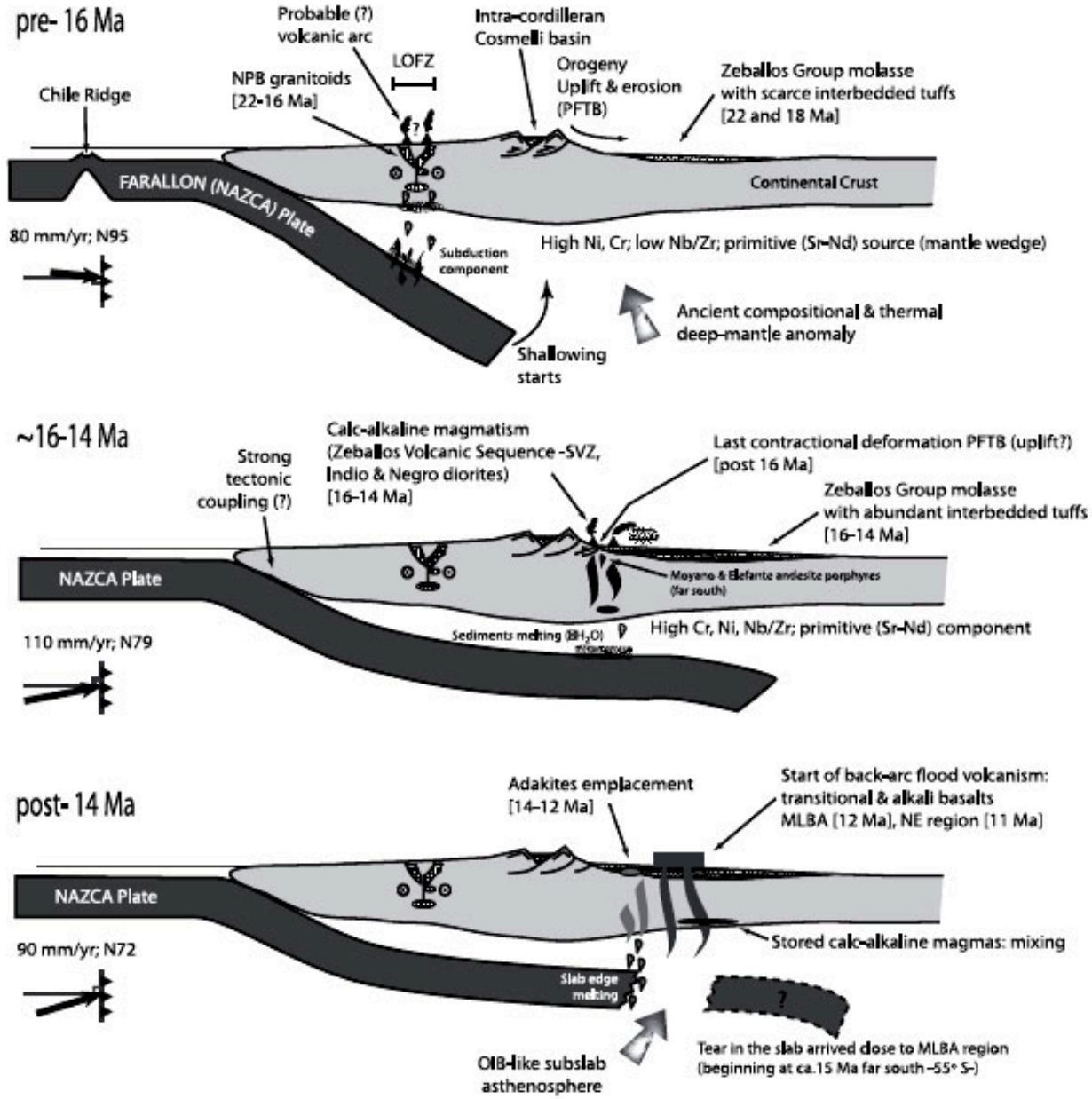
Region of Valdivia earthquake (1960)

GPS data

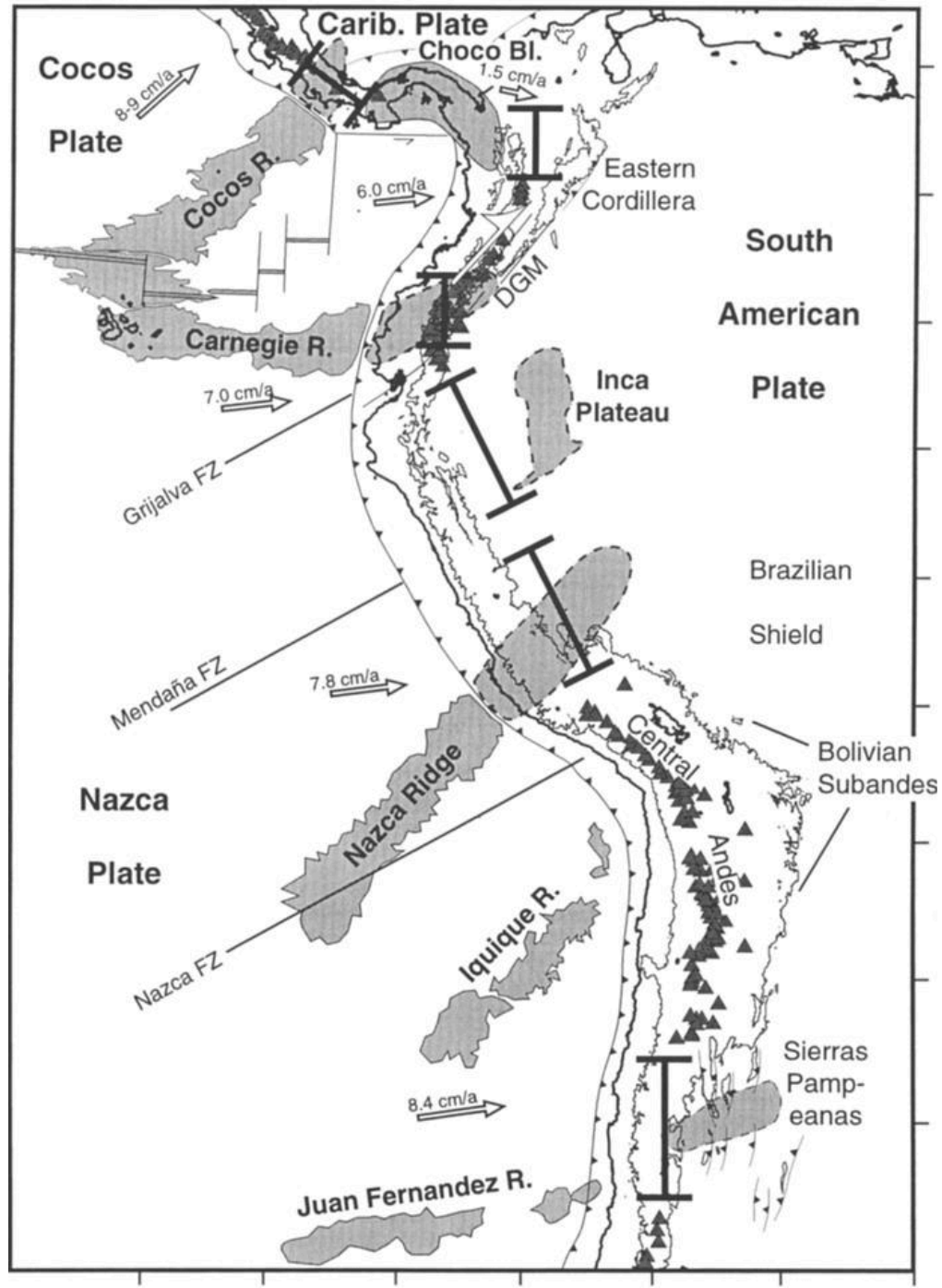
Magmatismo

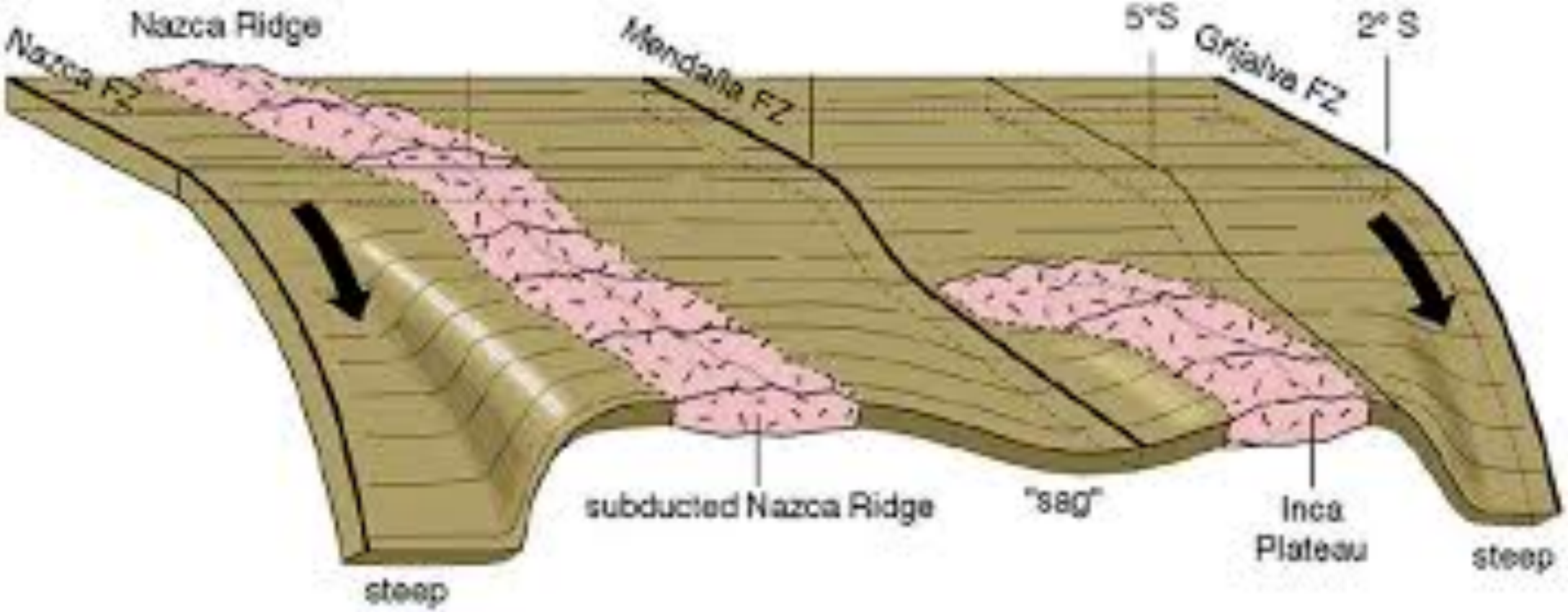


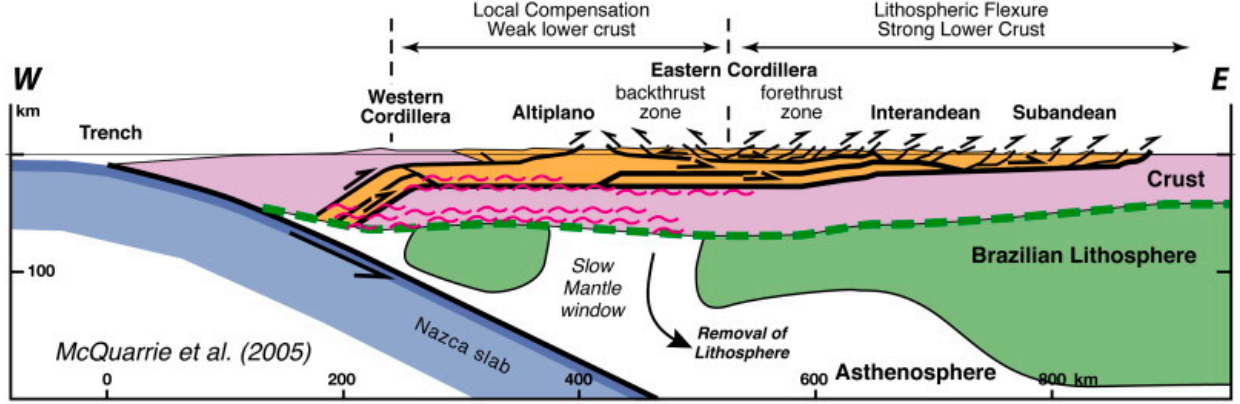
Modified from Wada and Wang, 2009

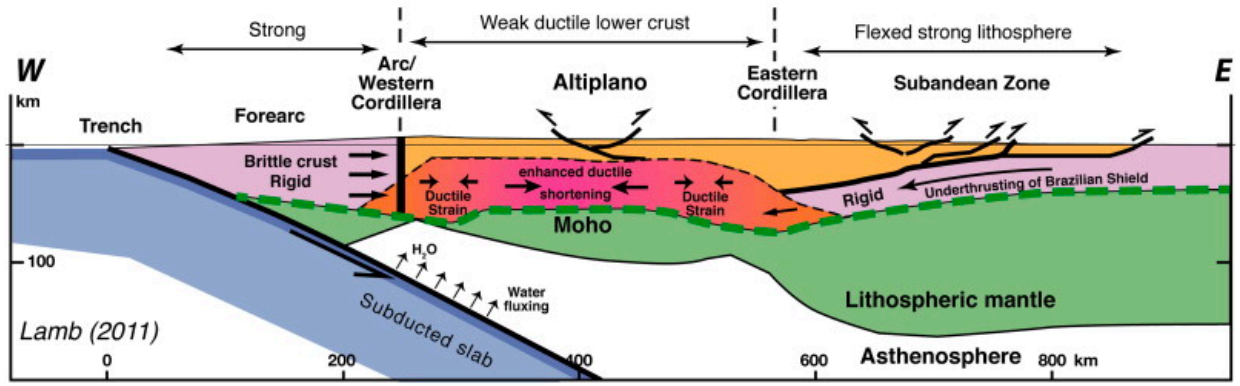


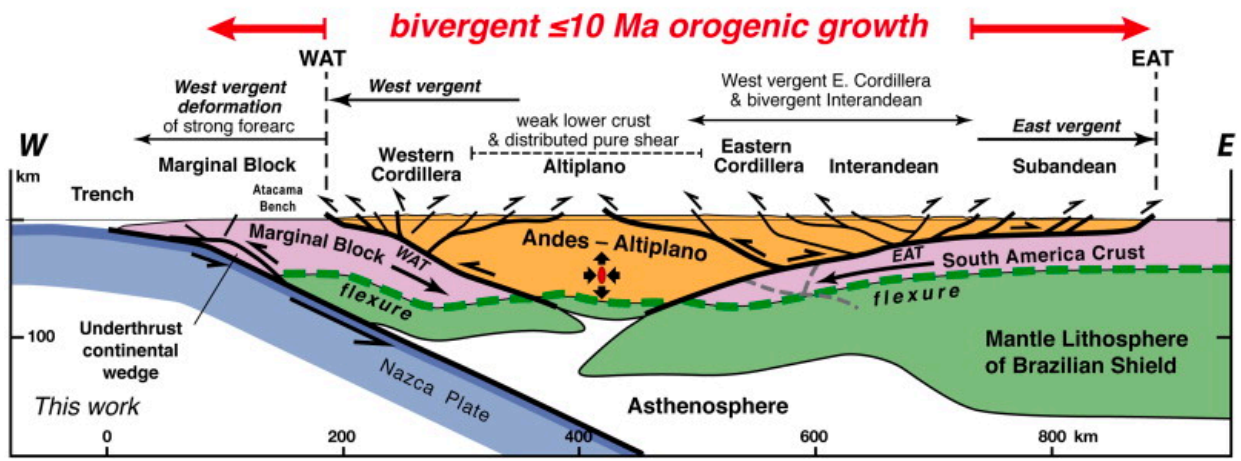
Espinoza et al. 2010 Andean Geology


Carib. Plate
Choco Bl.
Cocos
Plate
8-9 cm/a
1.5 cm/a
Cocos R.
6.0 cm/a
Eastern
Cordillera
South
American
Plate
DGM
Carnegie R.
Inca
Plateau
7.0 cm/a
Grijalva FZ
Brazilian
Shield
Mendaña FZ
7.8 cm/a
Central
Andes
Bolivian
Subandes
Nazca
Plate
Nazca Ridge
Iquique R.
Nazca FZ
Sierras
Pamp-
eanas
8.4 cm/a
Juan Fernandez R.

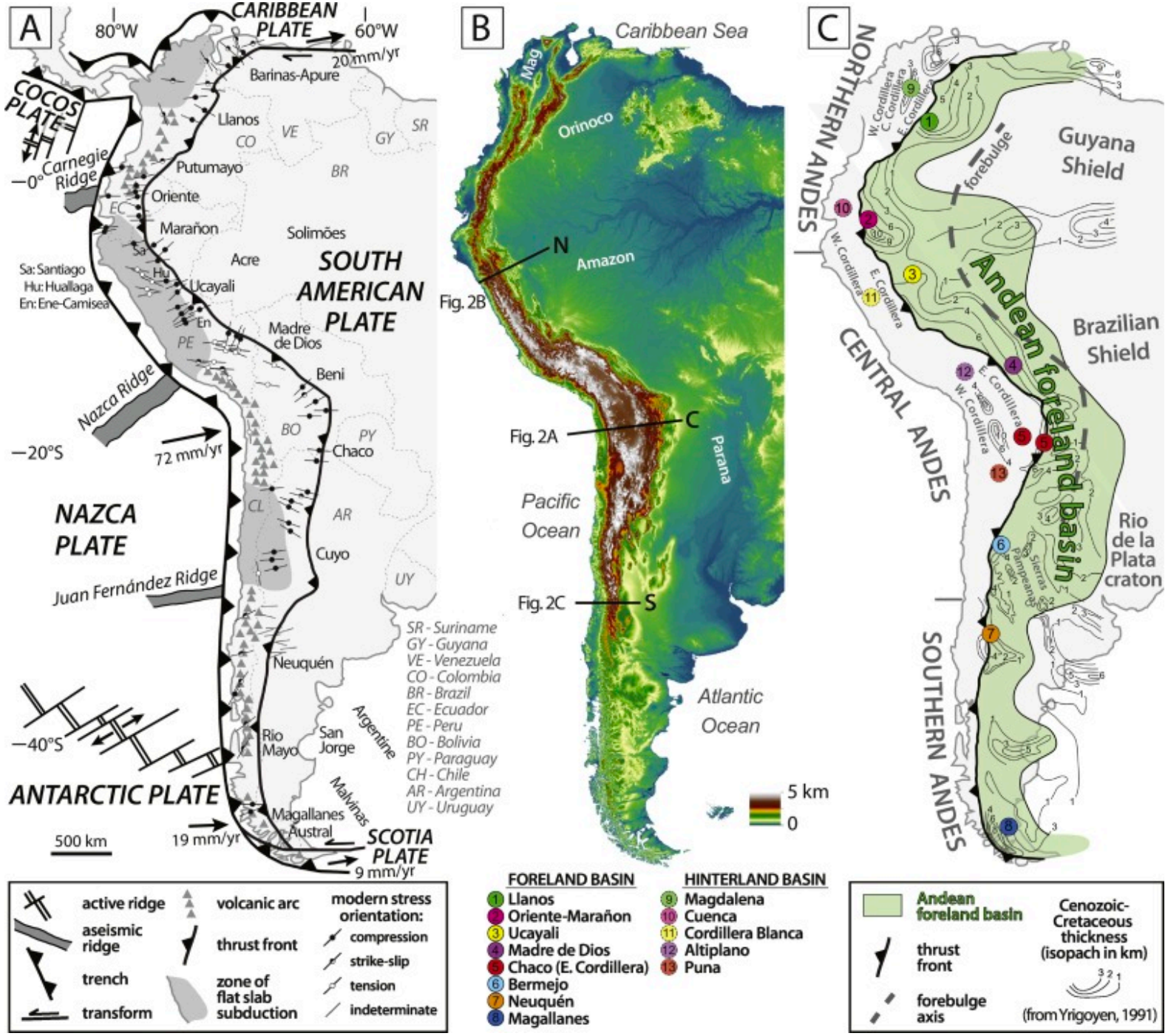

Nazca Ridge
Nazca FZ
Mendaña FZ
5°S
Grijalva FZ
2° S
subducted Nazca Ridge
"sag"
Inca Plateau
steep
steep


Local Compensation
Weak lower crust
Lithospheric Flexure
Strong Lower Crust
W
E
km
Eastern Cordillera
Western Cordillera
Altiplano
backthrust zone
forethrust zone
Interandean
Subandean
Trench
Crust
Brazilian Lithosphere
Slow Mantle window
Removal of Lithosphere
McQuarrie et al. (2005)
Nazca slab
Asthenosphere
100
0
200
400
600
800 km

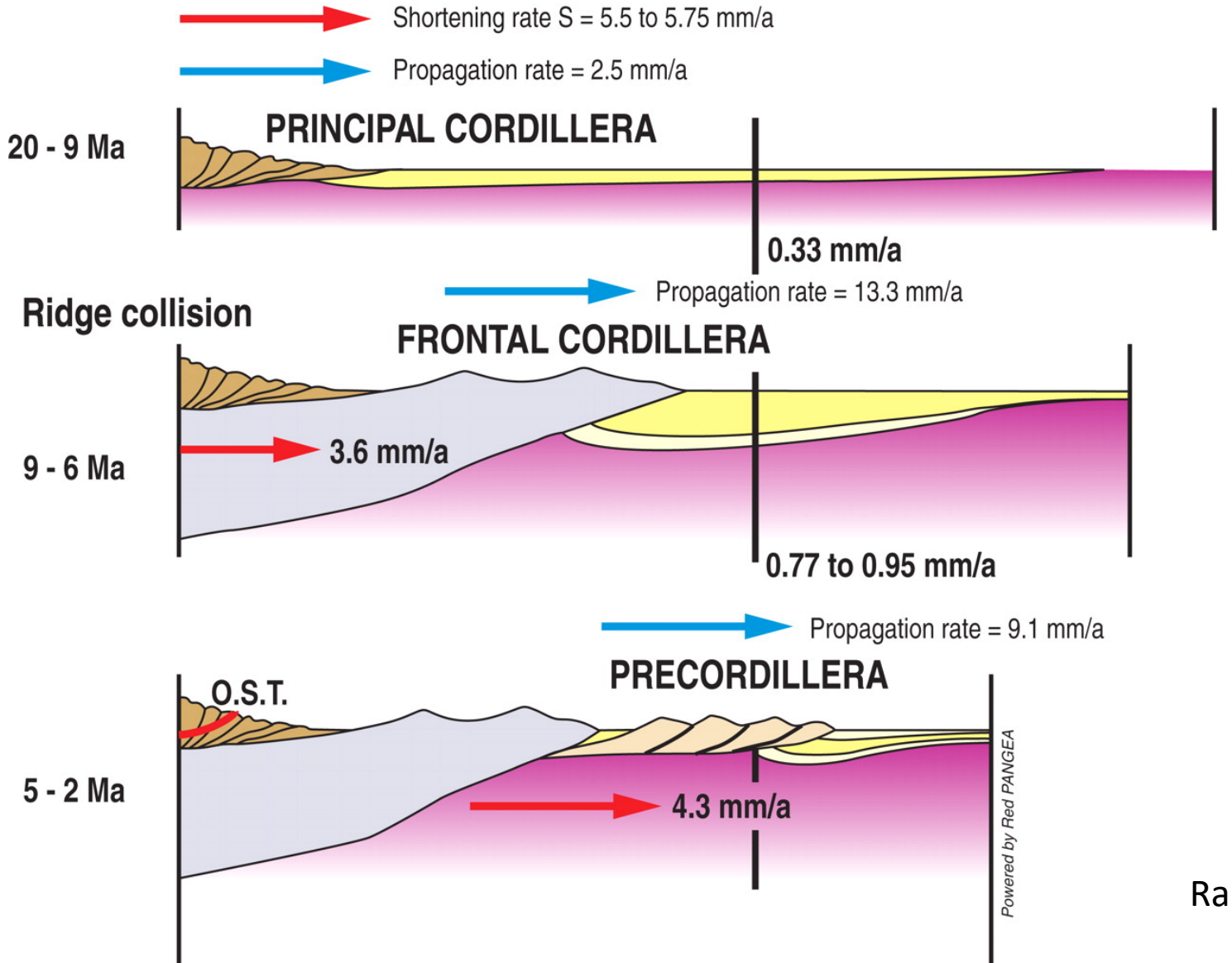

Strong
Weak ductile lower crust
Flexed strong lithosphere
W
E
km
Arc/ Western Cordillera
Altiplano
Eastern Cordillera
Subandean Zone
Trench
Forearc
Brittle crust
Rigid
enhanced ductile shortening
Ductile Strain
Ductile Strain
Rigid
Underthrusting of Brazilian Shield
Moho
H2O
Water fluxing
Lithospheric mantle
Lamb (2011)
Subducted slab
Asthenosphere
100
0
200
400
600
800 km


bivergent ≤10 Ma orogenic growth
WAT
EAT
West vergent deformation of strong forearc
West vergent
West vergent E. Cordillera & bivergent Interandean
weak lower crust & distributed pure shear
East vergent
W
E
km
Marginal Block
Western Cordillera
Altiplano
Eastern Cordillera
Interandean
Subandean
Trench
Atacama Bench
Marginal Block WAT
Andes – Altiplano
EAT
South America Crust
flexure
flexure
Underthrust continental wedge
Mantle Lithosphere of Brazilian Shield
This work
Nazca Plate
Asthenosphere
100
0
200
400
600
800 km

Sedimentação

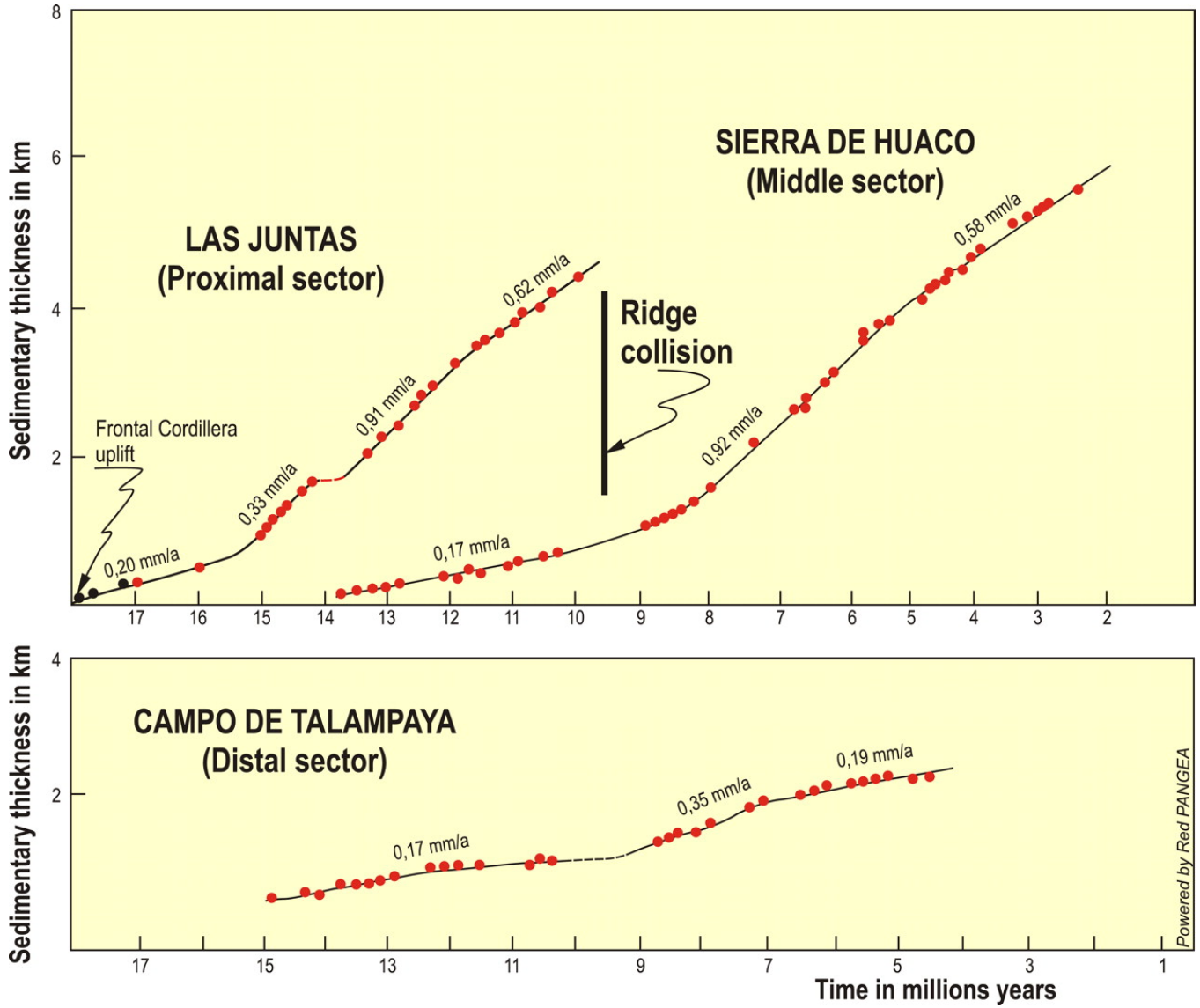

A
80°W
CARIBBEAN PLATE
60°W
20 mm/yr
Barinas-Apure
COCOS PLATE
Carnegie Ridge
0°
Llanos
CO
VE
GY
SR
Putumayo
BR
Oriente
EC
Marañon
Solimões
Sa
Hu
Acre
SOUTH AMERICAN PLATE
Sa: Santiago
Hu: Huallaga
En: Ene-Camisea
Ucayali
En
Madre de Dios
PE
Beni
Nazca Ridge
BO
PY
Chaco
20°S
72 mm/yr
NAZCA PLATE
CL
AR
Cuyo
Juan Fernández Ridge
UY
SR - Suriname
GY - Guyana
VE - Venezuela
CO - Colombia
BR - Brazil
EC - Ecuador
PE - Peru
BO - Bolivia
PY - Paraguay
CH - Chile
AR - Argentina
UY - Uruguay
Neuquén
40°S
Rio Mayo
San Jorge
Argentine
Malvinas
ANTARCTIC PLATE
Magallanes Austral
19 mm/yr
SCOTIA PLATE
9 mm/yr
500 km
active ridge
aseismic ridge
trench
transform
volcanic arc
thrust front
zone of flat slab subduction
modern stress orientation:
compression
strike-slip
tension
indeterminate
B
Caribbean Sea
Mag
Orinoco
N
Amazon
Fig. 2B
C
Fig. 2A
Parana
Pacific Ocean
Fig. 2C
S
Atlantic Ocean
5 km
0
FORELAND BASIN
1 Llanos
2 Oriente-Marañon
3 Ucayali
4 Madre de Dios
5 Chaco (E. Cordillera)
6 Bermejo
7 Neuquén
8 Magallanes
HINTERLAND BASIN
9 Magdalena
10 Cuenca
11 Cordillera Blanca
12 Altiplano
13 Puna
C
NORTHERN ANDES
W. Cordillera
C. Cordillera
E. Cordillera
forebulge
Guyana Shield
Andean foreland basin
Brazilian Shield
CENTRAL ANDES
Sierras Pampeanas
Rio de la Plata craton
SOUTHERN ANDES
Andean foreland basin
thrust front
forebulge axis
Cenozoic-Cretaceous thickness (isopach in km)
(from Yrigoyen, 1991)

The Aconcagua fold and thrust belt in the Central Andes at 32°S latitude with variations on shortening and propagation rates through time (after Ramos et al. 1996b and Hilley et al. 2004) and the subsidence rates in the foreland basin after Irigoyen et al.

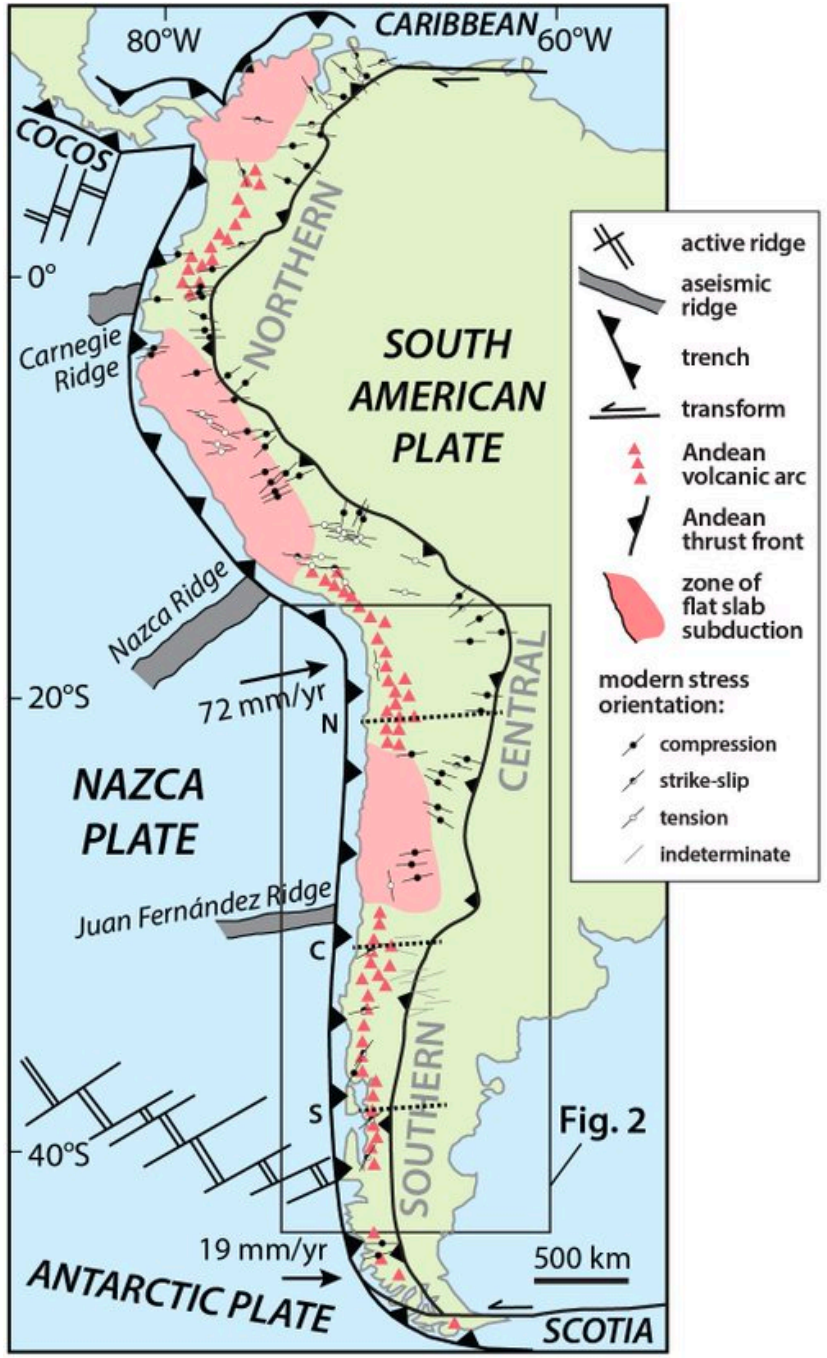


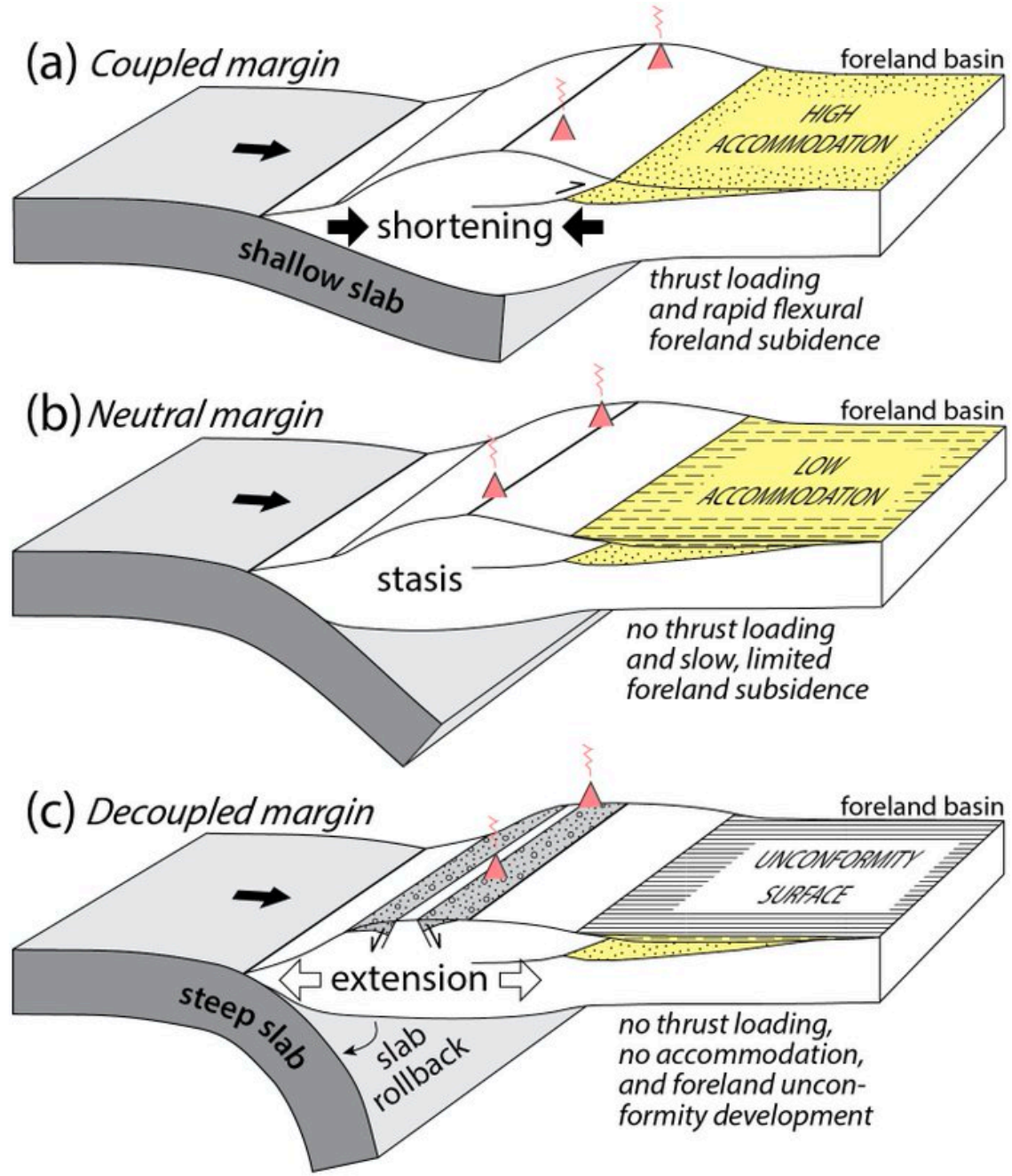
Ramos 2009 Geol Soc London

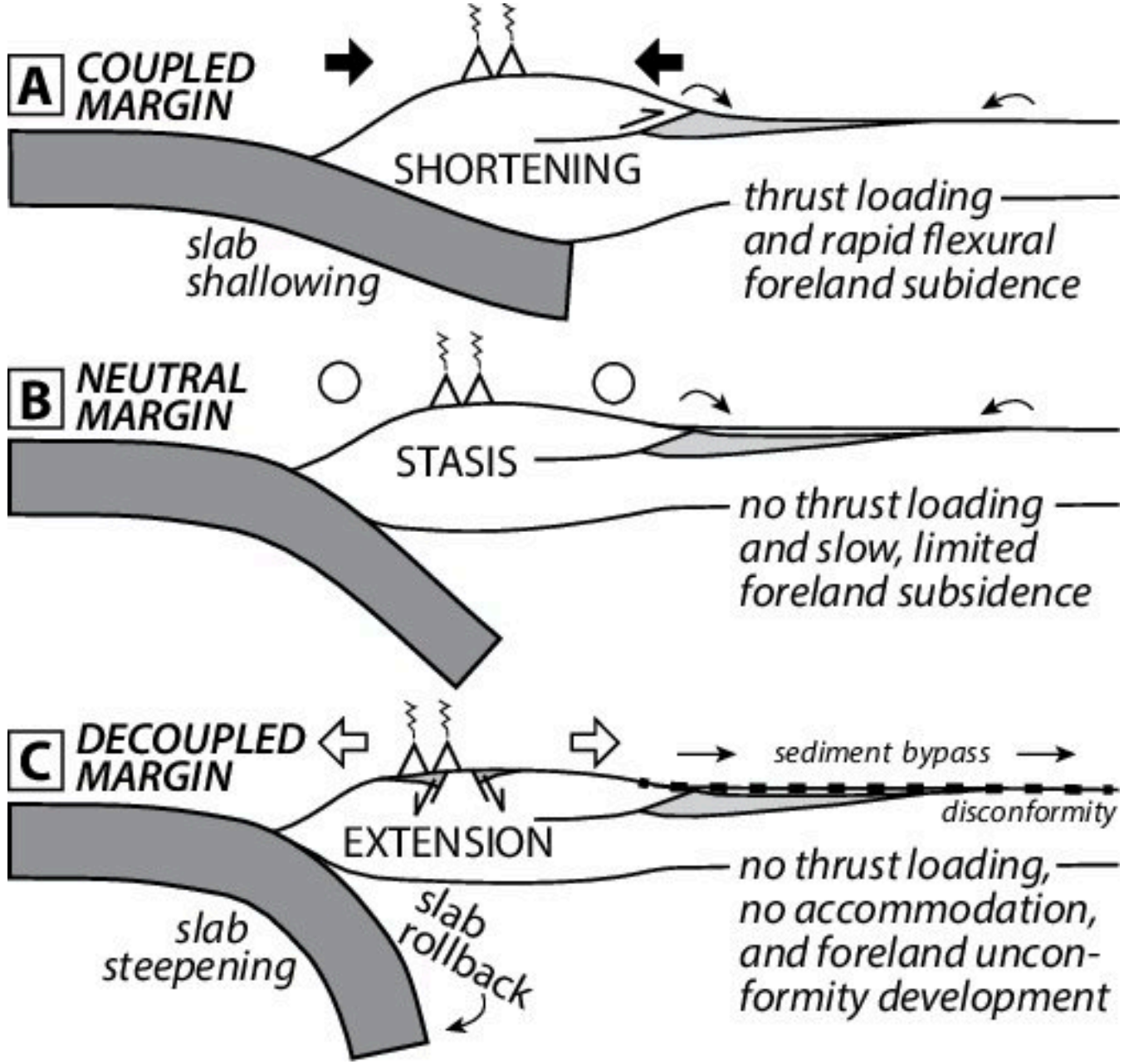
Subsidence rates in the proximal, intermediate and distal areas of the Bermejo broken foreland basin, with indication of the beginning of flat-slab subduction at these latitudes (modified from Ramos 1999b).



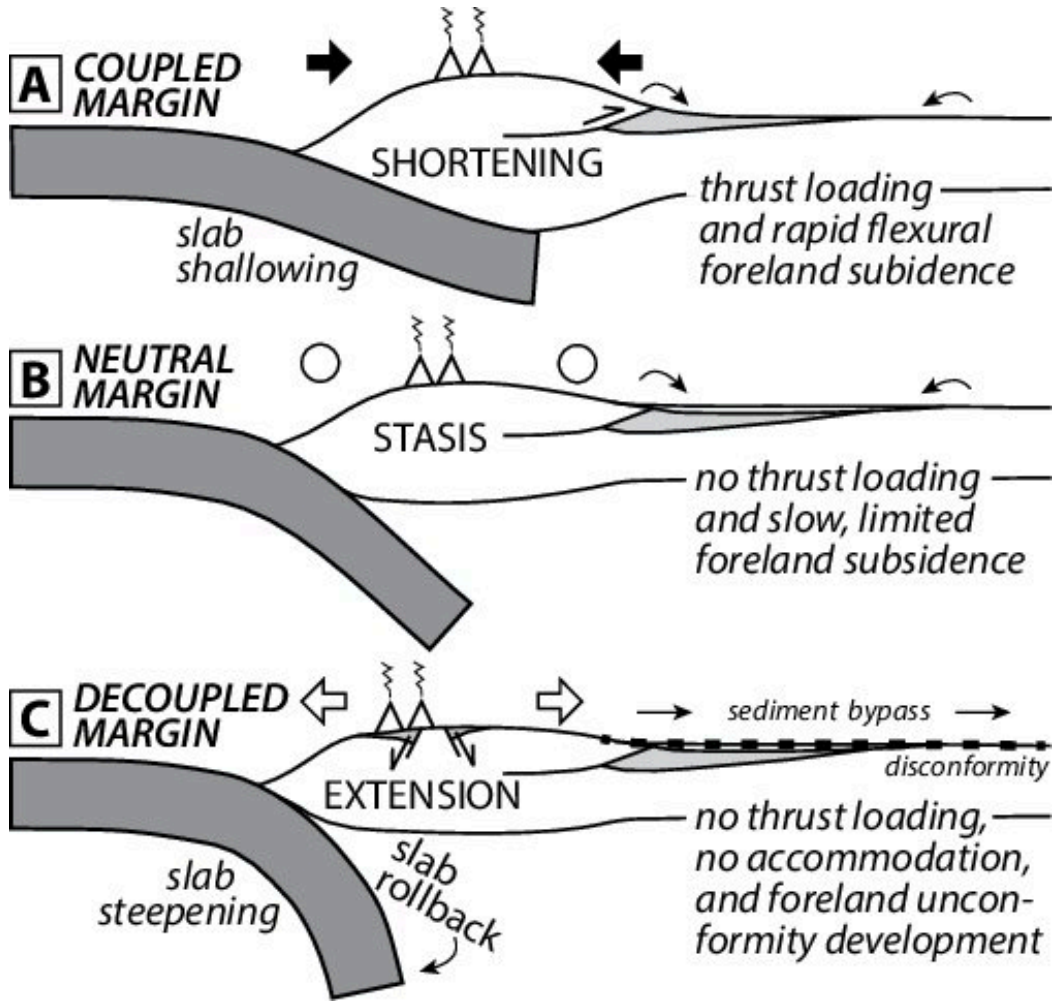
Ramos 2009 Geol Soc London

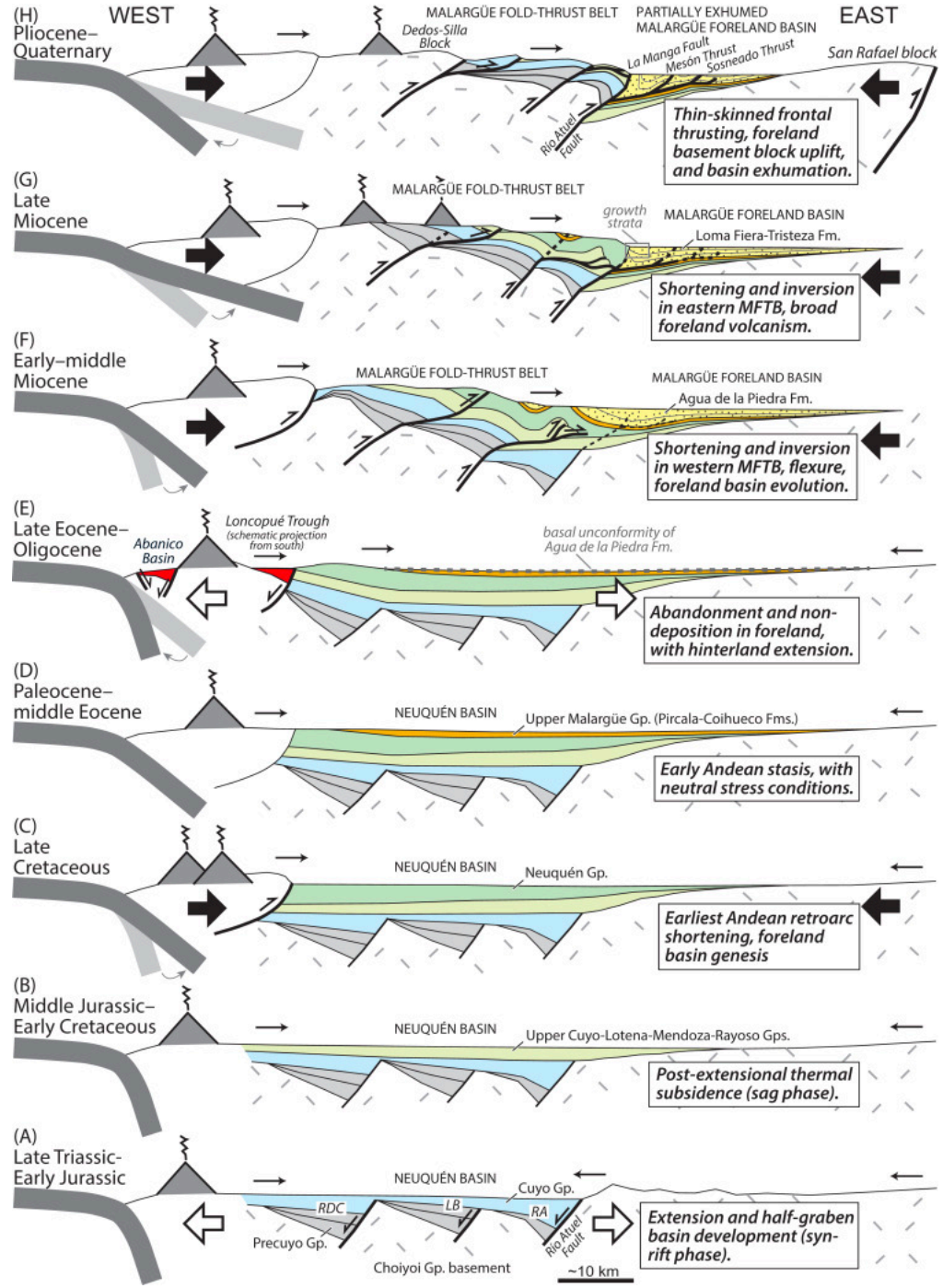

80°W
CARIBBEAN
60°W
COCOS
0°
Carnegie Ridge
NORTHERN
SOUTH AMERICAN PLATE
Nazca Ridge
20°S
72 mm/yr
N
CENTRAL
NAZCA PLATE
Juan Fernández Ridge
C
SOUTHERN
S
40°S
Fig. 2
19 mm/yr
500 km
ANTARCTIC PLATE
SCOTIA
active ridge
aseismic ridge
trench
transform
Andean volcanic arc
Andean thrust front
zone of flat slab subduction
modern stress orientation:
compression
strike-slip
tension
indeterminate


(a) Coupled margin
foreland basin
HIGH ACCOMMODATION
shortening
shallow slab
thrust loading and rapid flexural foreland subidence
(b) Neutral margin
foreland basin
LOW ACCOMMODATION
stasis
no thrust loading and slow, limited foreland subsidence
(c) Decoupled margin
foreland basin
UNCONFORMITY SURFACE
extension
steep slab
slab rollback
no thrust loading, no accommodation, and foreland unconformity development



Horton and Fuentes 2016. Geology


A COUPLED MARGIN
SHORTENING
slab shallowing
thrust loading and rapid flexural foreland subidence
B NEUTRAL MARGIN
STASIS
no thrust loading and slow, limited foreland subsidence
C DECOUPLED MARGIN
sediment bypass
disconformity
EXTENSION
slab steepening
slab rollback
no thrust loading, no accommodation, and foreland uncon-formity development


(H) Pliocene–Quaternary
WEST
MALARGÜE FOLD-THRUST BELT
PARTIALLY EXHUMED MALARGÜE FORELAND BASIN
EAST
Dedos-Silla Block
La Manga Fault
Mesón Thrust
Sosneado Thrust
San Rafael block
Río Atuel Fault
Thin-skinned frontal thrusting, foreland basement block uplift, and basin exhumation.
(G) Late Miocene
MALARGÜE FOLD-THRUST BELT
growth strata
MALARGÜE FORELAND BASIN
Loma Fiera-Tristeza Fm.
Shortening and inversion in eastern MFTB, broad foreland volcanism.
(F) Early–middle Miocene
MALARGÜE FOLD-THRUST BELT
MALARGÜE FORELAND BASIN
Agua de la Piedra Fm.
Shortening and inversion in western MFTB, flexure, foreland basin evolution.
(E) Late Eocene–Oligocene
Abanico Basin
Loncopué Trough (schematic projection from south)
basal unconformity of Agua de la Piedra Fm.
Abandonment and non-deposition in foreland, with hinterland extension.
(D) Paleocene–middle Eocene
NEUQUÉN BASIN
Upper Malargüe Gp. (Pircala-Coihueco Fms.)
Early Andean stasis, with neutral stress conditions.
(C) Late Cretaceous
NEUQUÉN BASIN
Neuquén Gp.
Earliest Andean retroarc shortening, foreland basin genesis
(B) Middle Jurassic–Early Cretaceous
NEUQUÉN BASIN
Upper Cuyo-Lotena-Mendoza-Rayoso Gps.
Post-extensional thermal subsidence (sag phase).
(A) Late Triassic-Early Jurassic
NEUQUÉN BASIN
Cuyo Gp.
RDC
LB
RA
Río Atuel Fault
Precuyo Gp.
Choiyoi Gp. basement
~10 km
Extension and half-graben basin development (syn-rift phase).

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The tectonic regime along the Andes: Present-day and Mesozoic regimes

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Estudo dirigido, Geologia dos Andes (Ramos, 2010).

1) Quais são os principais parâmetros que controlam a geometria e o contexto tectônico de zonas de subducção do tipo Andino?

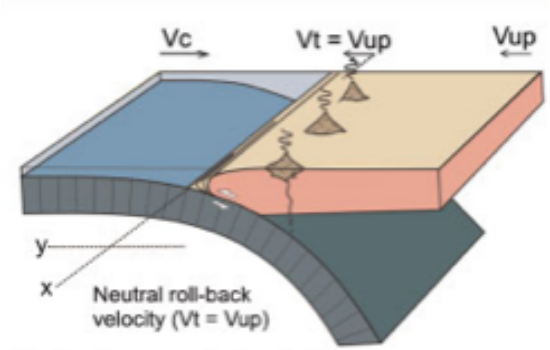
2) Descreva as geometrias das margens continentais em função do movimento absoluto das placas (velocidade de roll-back na trincheira).

3) Descreva as principais características (movimentação da placa subductante, magmatismo, deformação no arco, atrás e na frente do arco), das seguintes margens convergentes: Nicarágua, South Sandwich, Oregon, Chile.

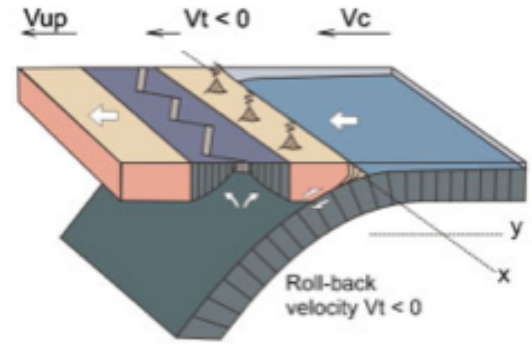
4) Quais os principais características geológicas das regiões onde dominou extensão ao longo da margem Andina?

5) Quais os principais características geológicas das regiões onde dominou compressão ao longo da margem Andina?

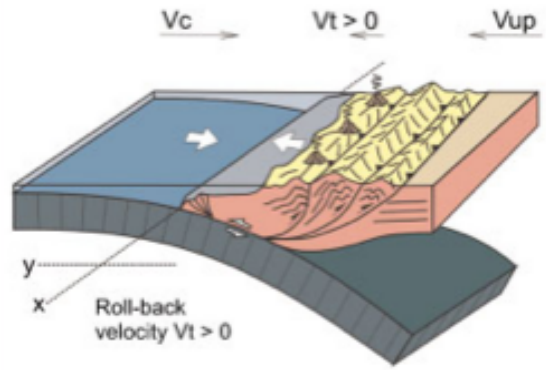
6) Existe deformação transcorrente ao longo da margem Andina? Como e por que ela ocorre?



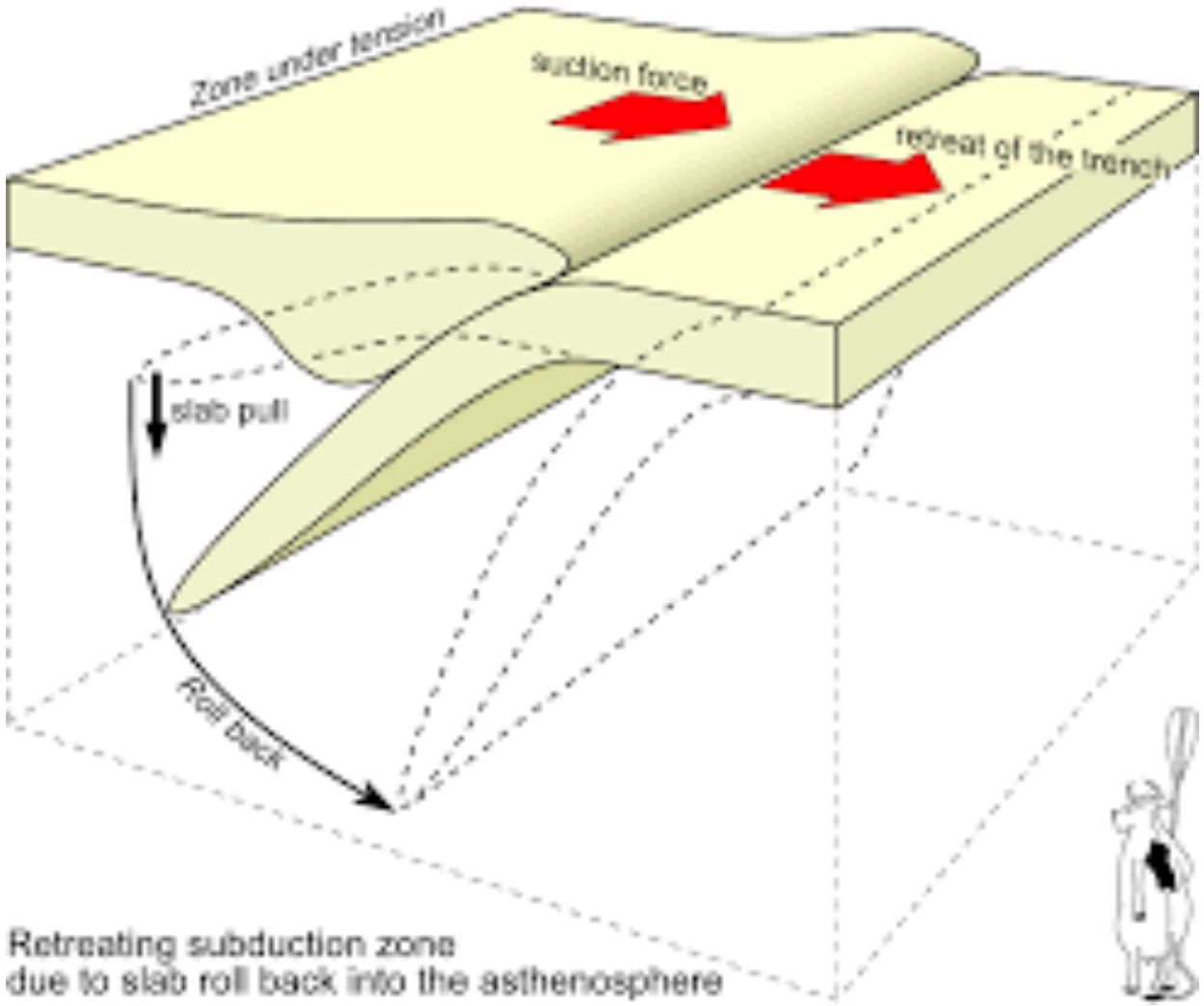
(a) **Stationary subduction hinge**

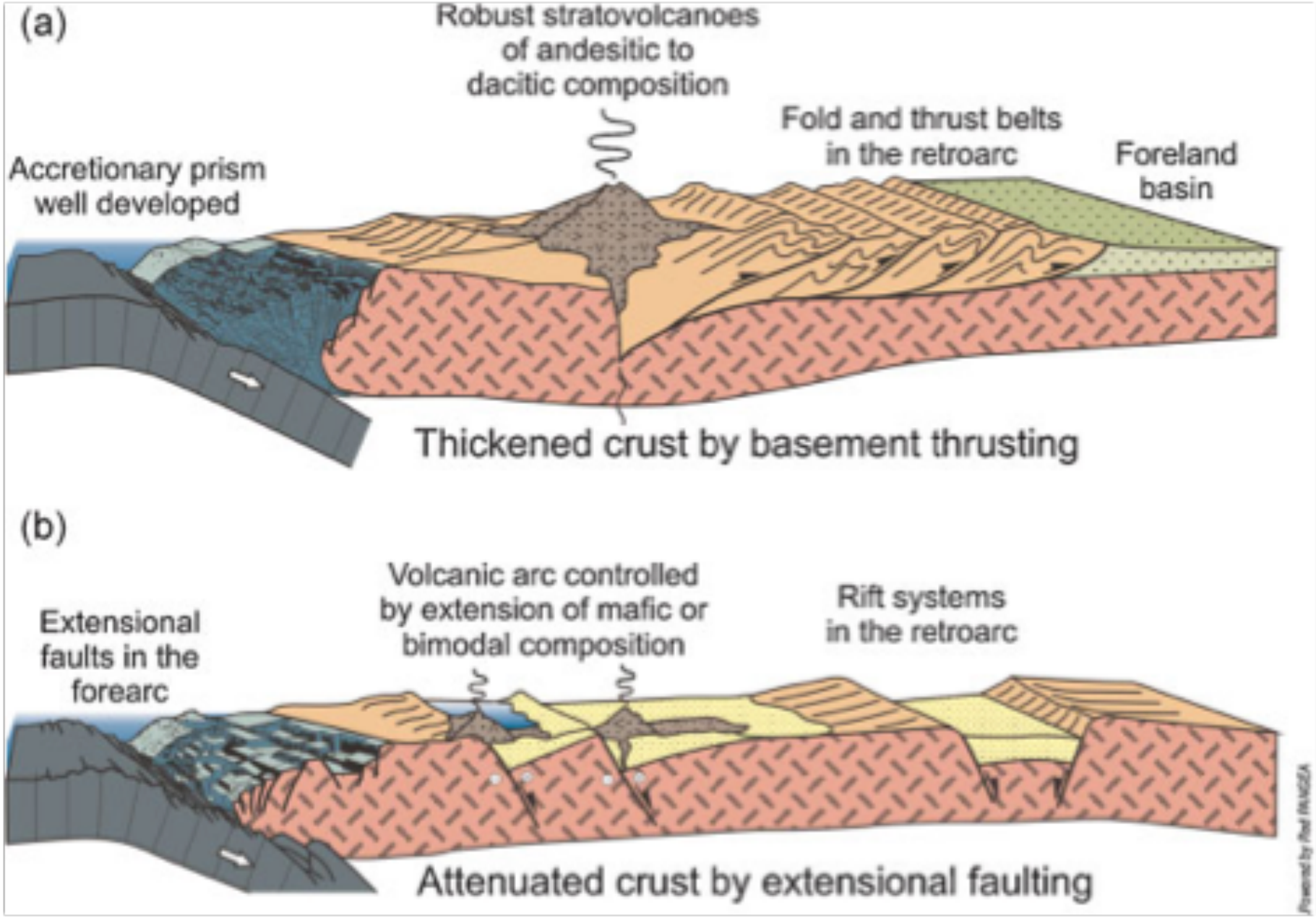


(b) **Retreating subduction hinge**



(c) **Forward migrating subduction hinge**




(a)
Robust stratovolcanoes of andesitic to dacitic composition
Fold and thrust belts in the retroarc
Foreland basin
Accretionary prism well developed
Thickened crust by basement thrusting
(b)
Volcanic arc controlled by extension of mafic or bimodal composition
Rift systems in the retroarc
Extensional faults in the forearc
Attenuated crust by extensional faulting

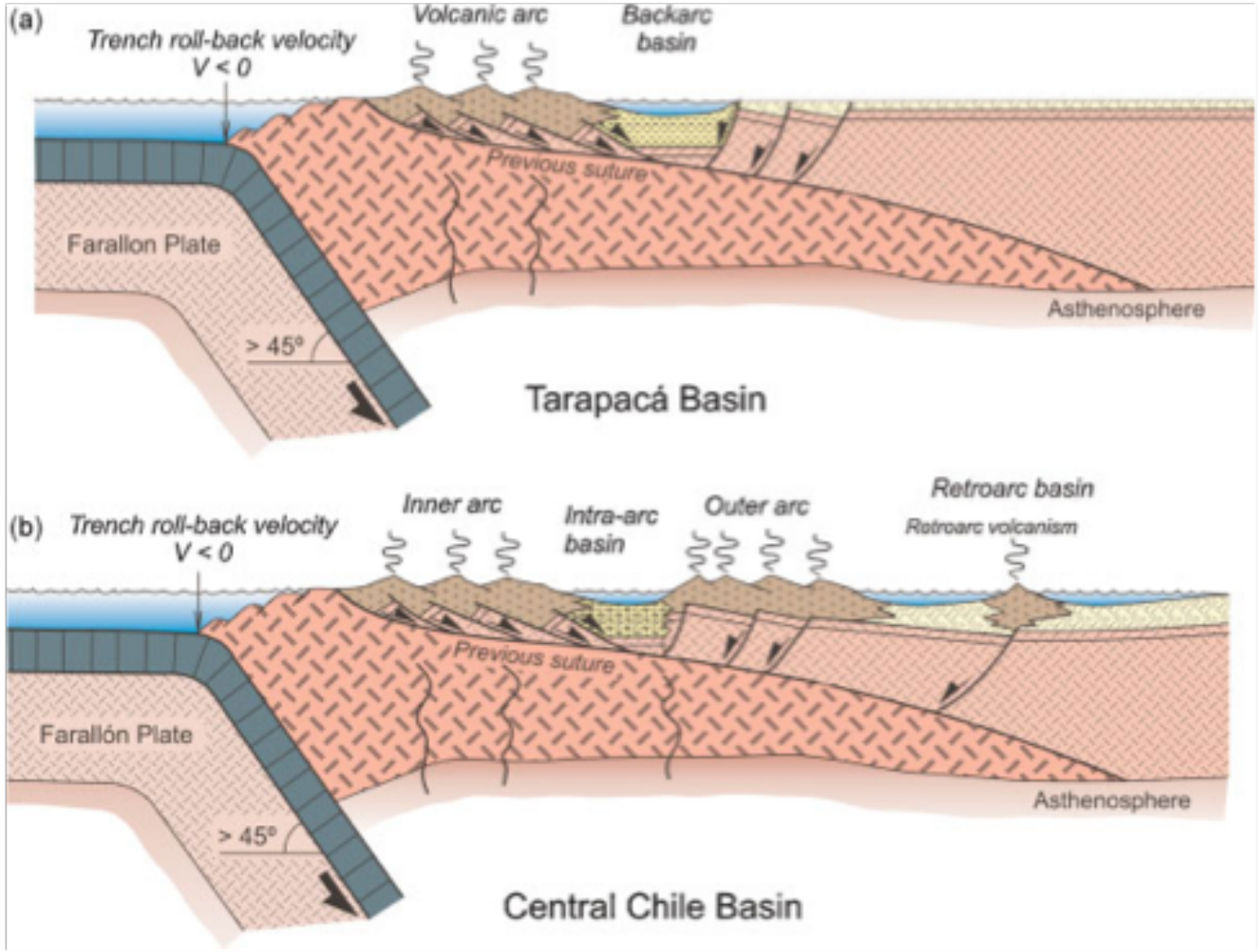
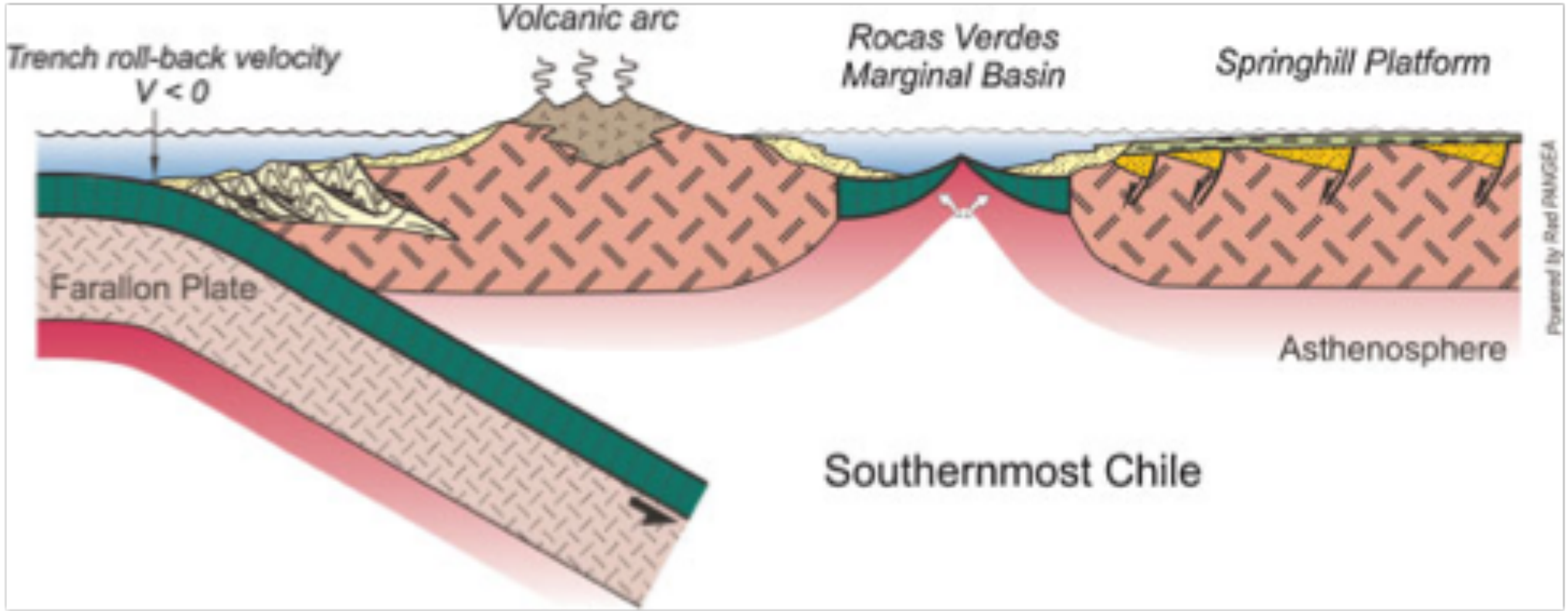
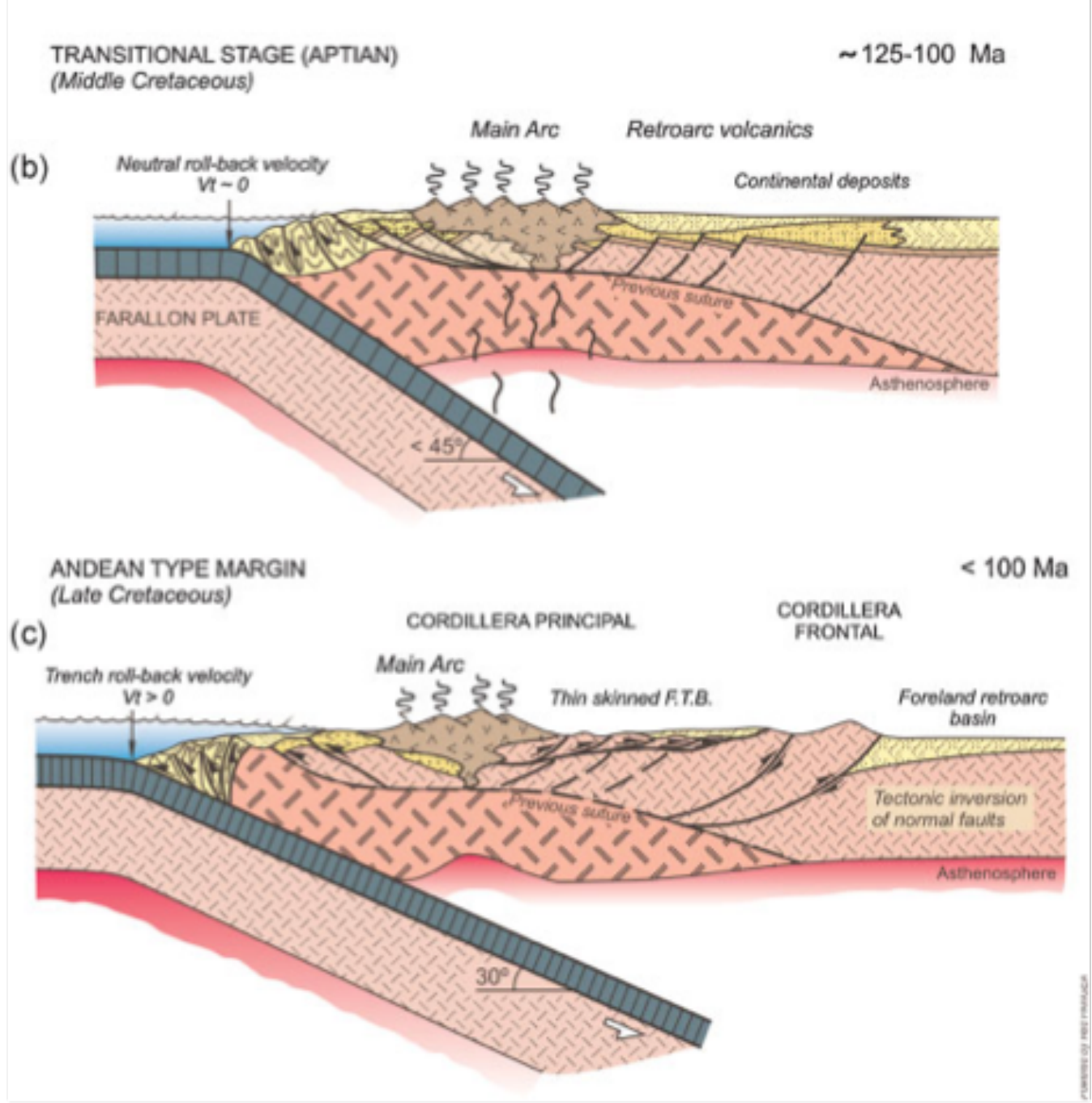


Figure 12. Palaeogeographic reconstruction of the Tarapacá Basin in northern Chile and Central Chile Basin at the latitude of the Aconcagua (based on Mpodozis and Ramos 2008) (see location in Figure 9).


Volcanic arc
Trench roll-back velocity
V < 0
Rocas Verdes
Marginal Basin
Springhill Platform
Farallon Plate
Asthenosphere
Southernmost Chile
Powered by Red PANGEA


TRANSITIONAL STAGE (APTIAN)
(Middle Cretaceous)
~125-100 Ma
(b)
Main Arc
Retroarc volcanics
Neutral roll-back velocity
Vt ~ 0
Continental deposits
Previous suture
FARALLON PLATE
Asthenosphere
< 45°
ANDEAN TYPE MARGIN
(Late Cretaceous)
< 100 Ma
(c)
CORDILLERA PRINCIPAL
CORDILLERA FRONTAL
Main Arc
Trench roll-back velocity
Vt > 0
Thin skinned F.T.B.
Foreland retroarc basin
Previous suture
Tectonic inversion of normal faults
Asthenosphere
30°

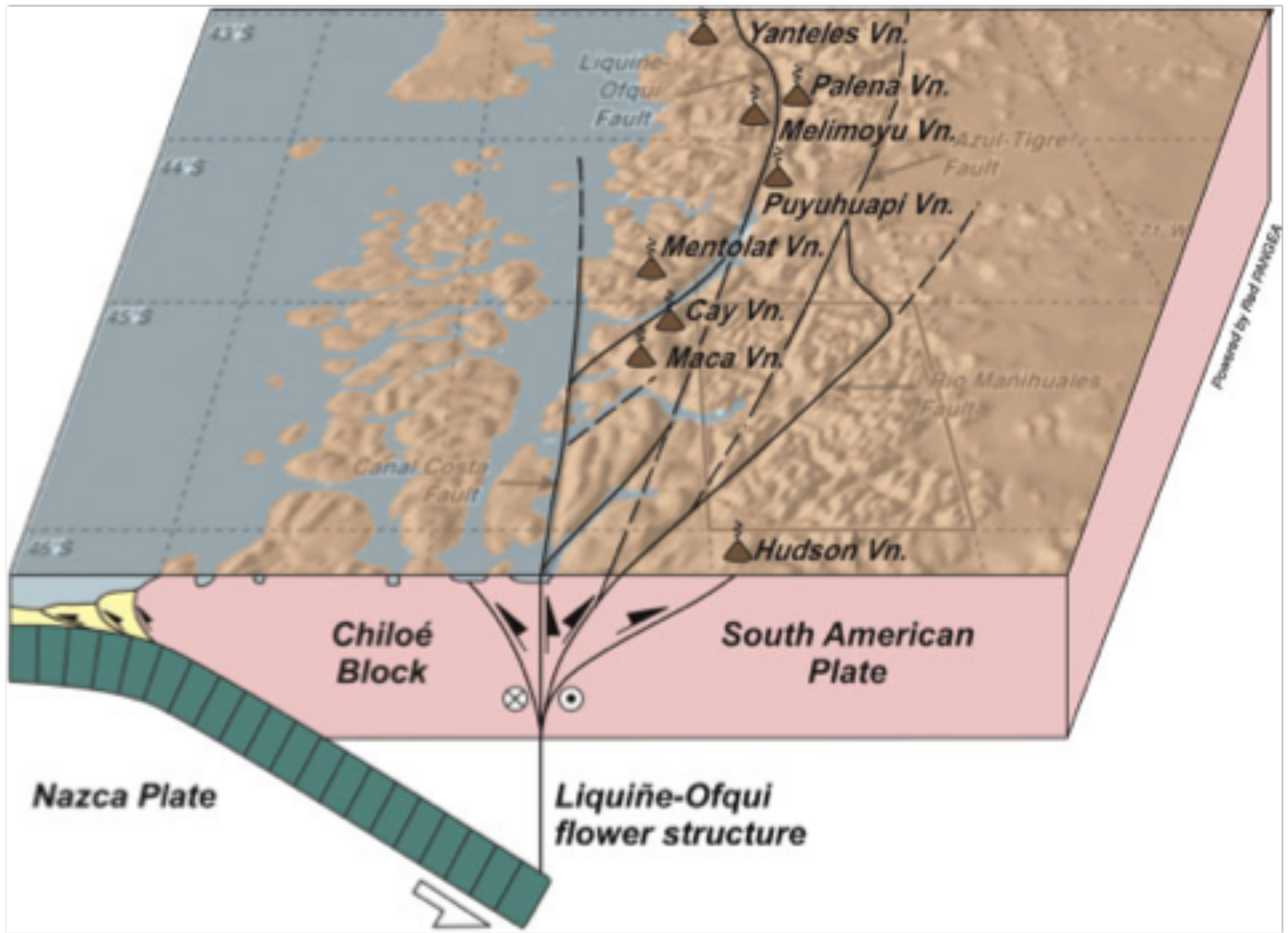


Figure 16. Strike-slip deformation along the Liquiñe–Ofqui Fault in southern Chile based on Thomson (2002). Note the concentration of the arc volcanoes along the main fault zone.

The present subduction of the eastern Pacific along the Americas shows different tectonic regimes that have been exemplified in four subduction zones:

(1) *Nicaragua subduction zone*: an extensional regime in the upper plate associated with poorly evolved continental magmatic arc, extensional back-arc and rift basins developed in continental crust.
(2) *Sandwich subduction zone*: an extensional regime in the upper plate associated with an island arc developed in oceanic crust and formation of an extensional oceanic floored back-arc basin controlled by the eastward mantle flow.
(3) *Oregon subduction zone*: a neutral to mildly deformed upper plate that can be interpreted as an early stage of the Chile-type subduction, associated with a volcanic arc with no contraction controlled by the almost stationary trench roll-back velocity, due to the young age of the oceanic crust subducted and the small absolute motion of the upper plate.
(4) *Chile-type*: a severe to mild compressional regime associated with a highly to moderate evolved magmatic arc, fold and thrust belt development and foreland basin formation along a continental margin with important deformation associated with the westwards absolute motion relative to the hotspot frame of the upper plate that overrides the trench.

ARTICLE

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South-American plate advance and forced Andean trench retreat as drivers for transient flat subduction episodes

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Estudo dirigido, Geologia dos Andes (Schepers et al., 2017).

1) Qual a principal força atuante na tectônica de placas?

2) Quais os mecanismos propostos para ocorrência de subducção rasa nos Andes? Por que esse processo é contra-intuitivo?

3) Como Schepers et al. estimaram o encurtamento na cadeia dos Andes, a quantidade de litosfera subductada em ângulo raso e o recuo da trincheira?

4) Qual o modelo proposto pelos autores para a manutenção da subducção rasa nos Andes? Por que esse modelo é preferível àquele de subducção de uma crosta oceânica menos densa?

5) Em quais outros locais do globo que este modelo pode ser aplicado?

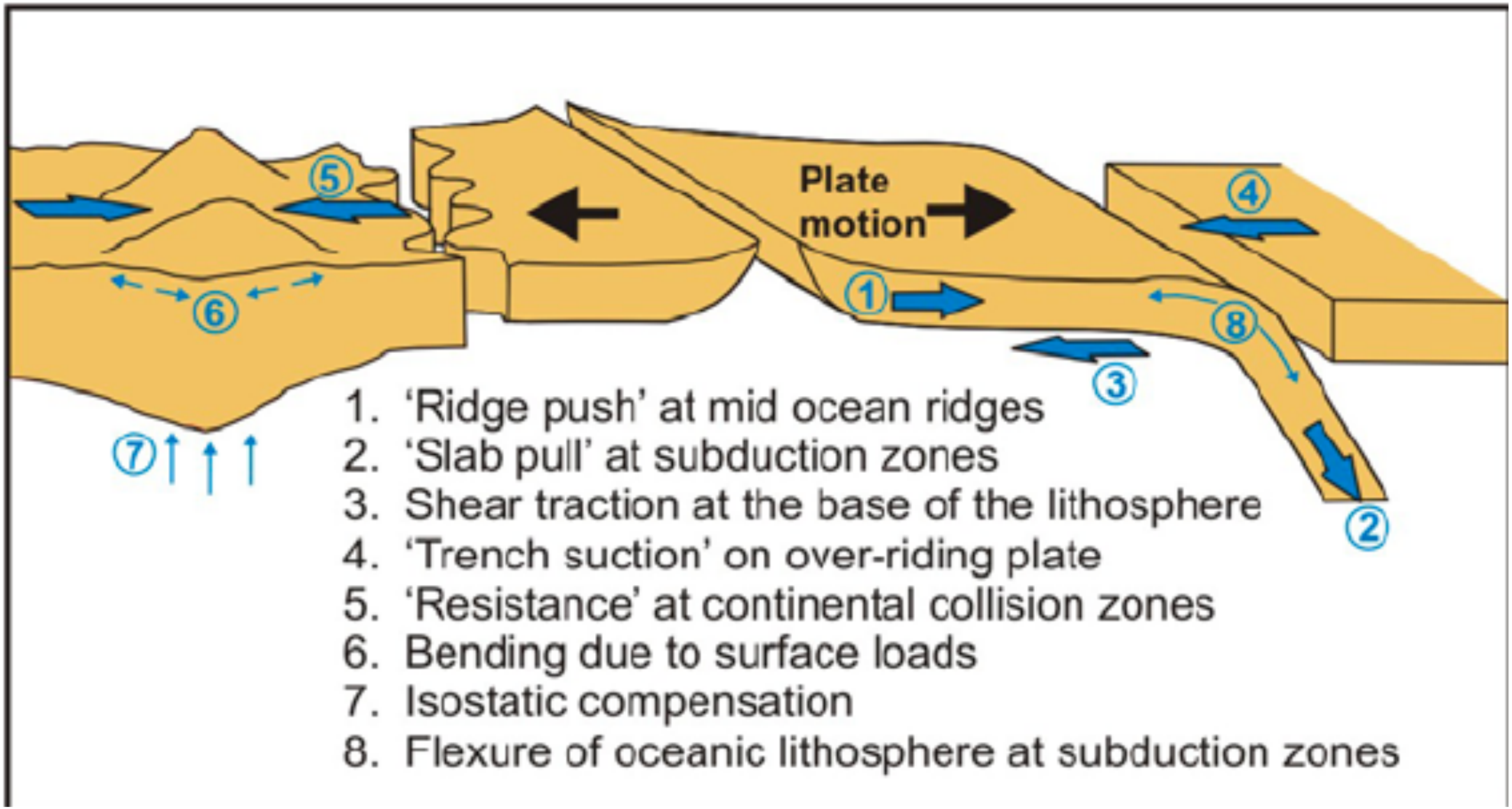
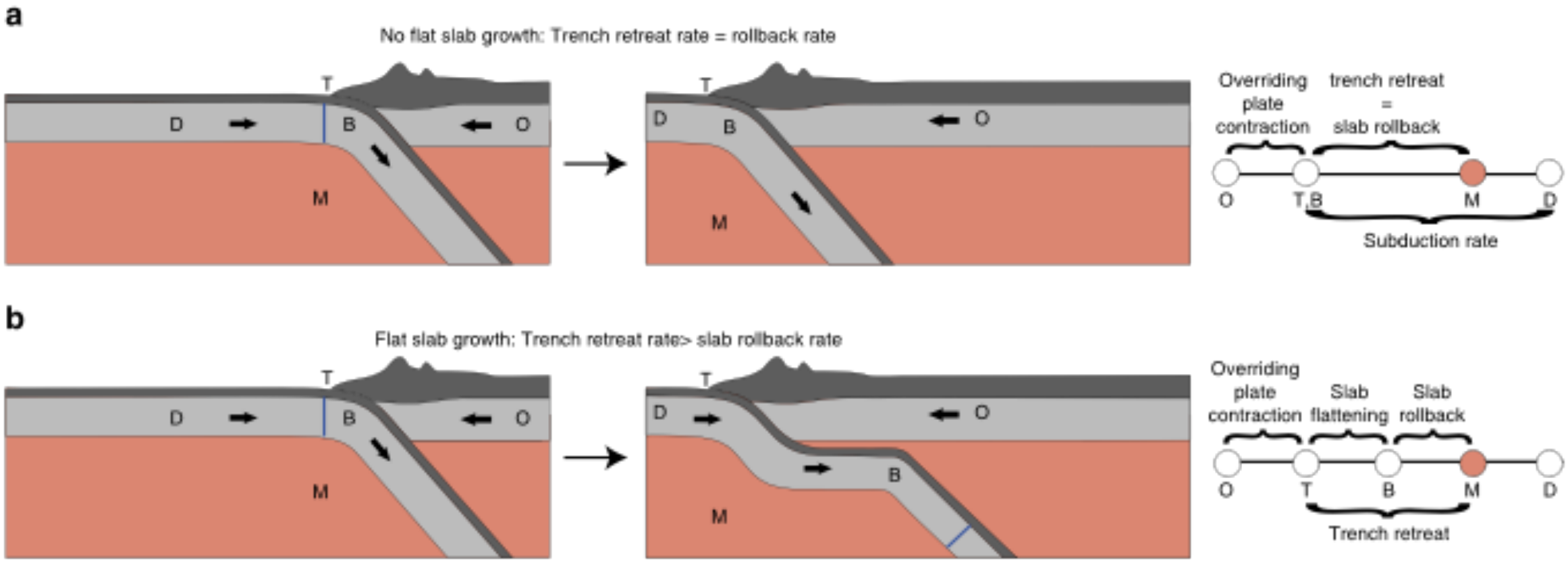
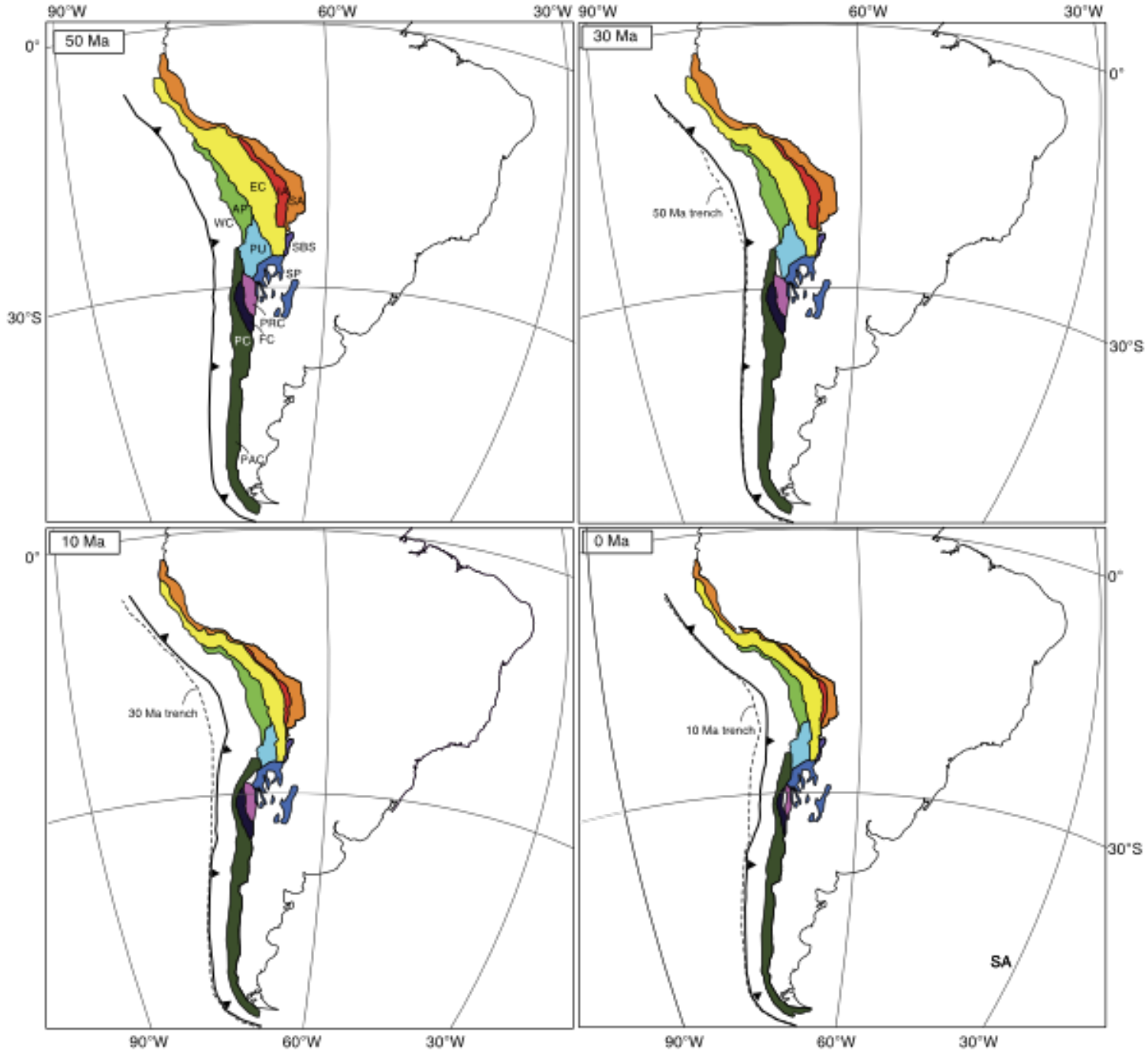
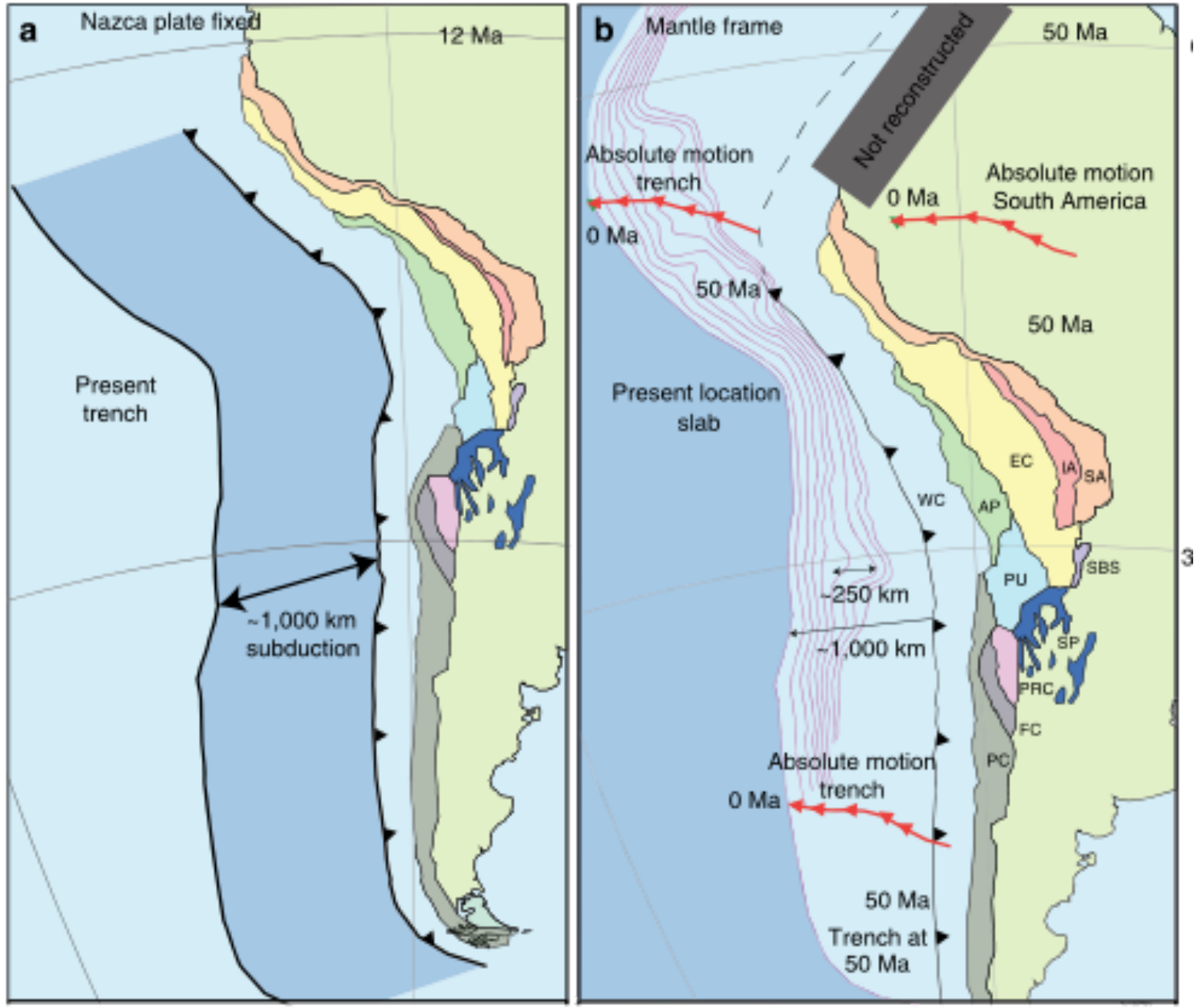


Plate
motion
1. ‘Ridge push’ at mid ocean ridges
2. ‘Slab pull’ at subduction zones
3. Shear traction at the base of the lithosphere
4. ‘Trench suction’ on over-riding plate
5. ‘Resistance’ at continental collision zones
6. Bending due to surface loads
7. Isostatic compensation
8. Flexure of oceanic lithosphere at subduction zones


a
No flat slab growth: Trench retreat rate = rollback rate
T
D
B
O
M
Overriding plate contraction
trench retreat = slab rollback
O
T,B
M
D
Subduction rate
b
Flat slab growth: Trench retreat rate> slab rollback rate
Overriding plate contraction
Slab flattening
Slab rollback
T
B
Trench retreat


90°W
60°W
30°W
0°
30°S
50 Ma
EC
SA
AP
WC
PU
SBS
SP
PRC
PC
FC
PAC
30 Ma
50 Ma trench
10 Ma
30 Ma trench
0 Ma
10 Ma trench
SA


a
Nazca plate fixed
12 Ma
Present
trench
~1,000 km
subduction
b
Mantle frame
50 Ma
Not reconstructed
Absolute motion
trench
0 Ma
Absolute motion
South America
0 Ma
50 Ma
50 Ma
Present location
slab
EC
IA
SA
WC
AP
SBS
PU
~250 km
~1,000 km
SP
PRC
FC
PC
Absolute motion
trench
0 Ma
50 Ma
Trench at
50 Ma

Patagônia

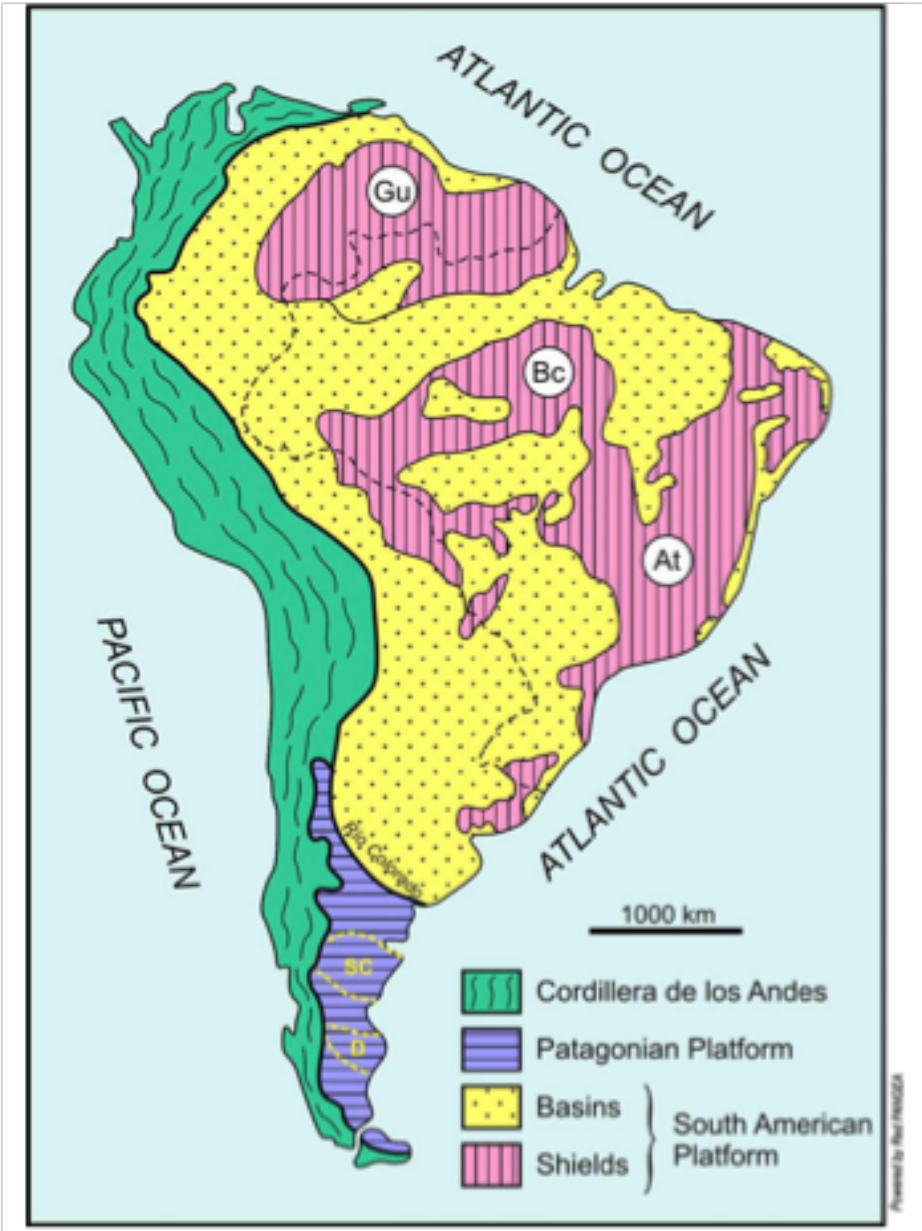


Fig. 1. Regional location of the Patagonia Platform with most important basement massifs: the Deseado (D) and Somún Cura (SC). Gu: Guyana, Bc: Brasil Central, At: Atlántico (based on Almeida et al., 1976).

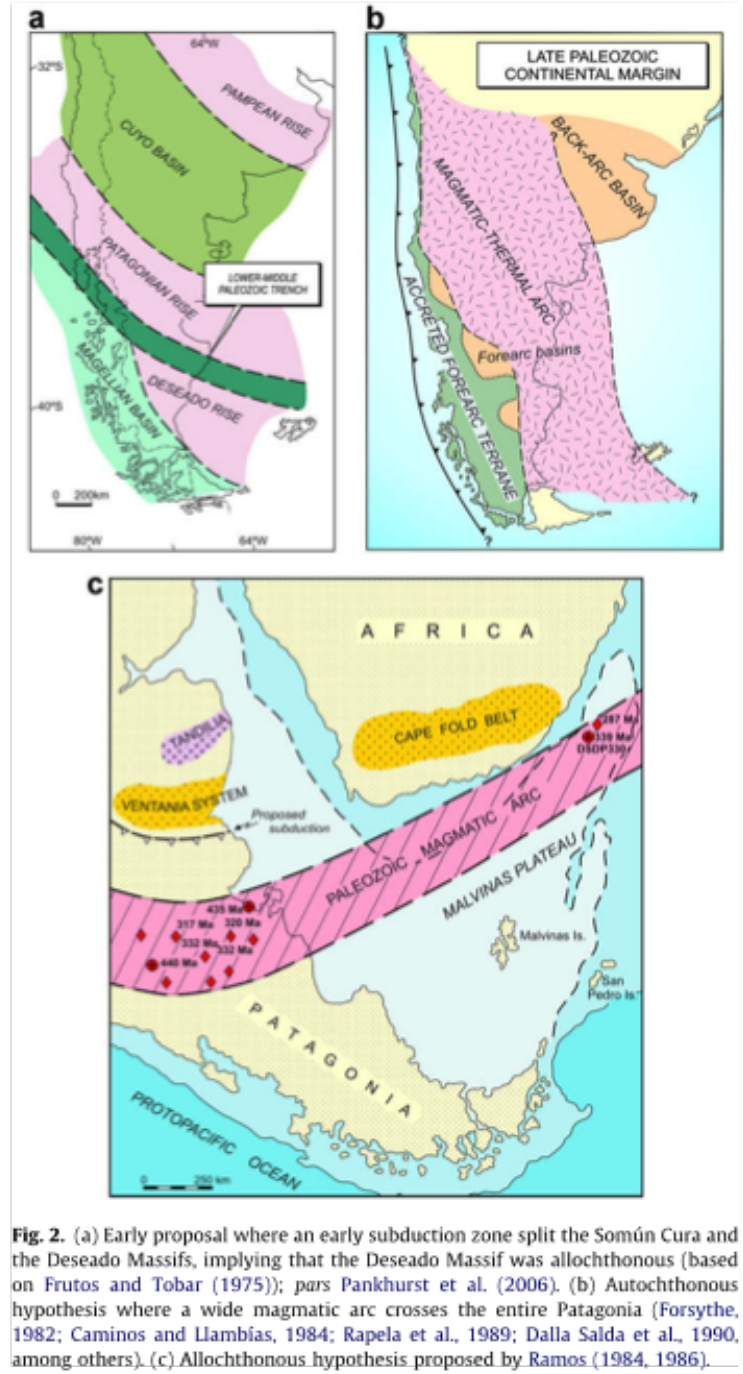


Fig. 2. (a) Early proposal where an early subduction zone split the Somún Cura and the Deseado Massifs, implying that the Deseado Massif was allochthonous (based on Frutos and Tobar (1975)); *pars* Pankhurst et al. (2006). (b) Autochthonous hypothesis where a wide magmatic arc crosses the entire Patagonia (Forsythe, 1982; Caminos and Llambías, 1984; Rapela et al., 1989; Dalla Salda et al., 1990, among others). (c) Allochthonous hypothesis proposed by Ramos (1984, 1986).

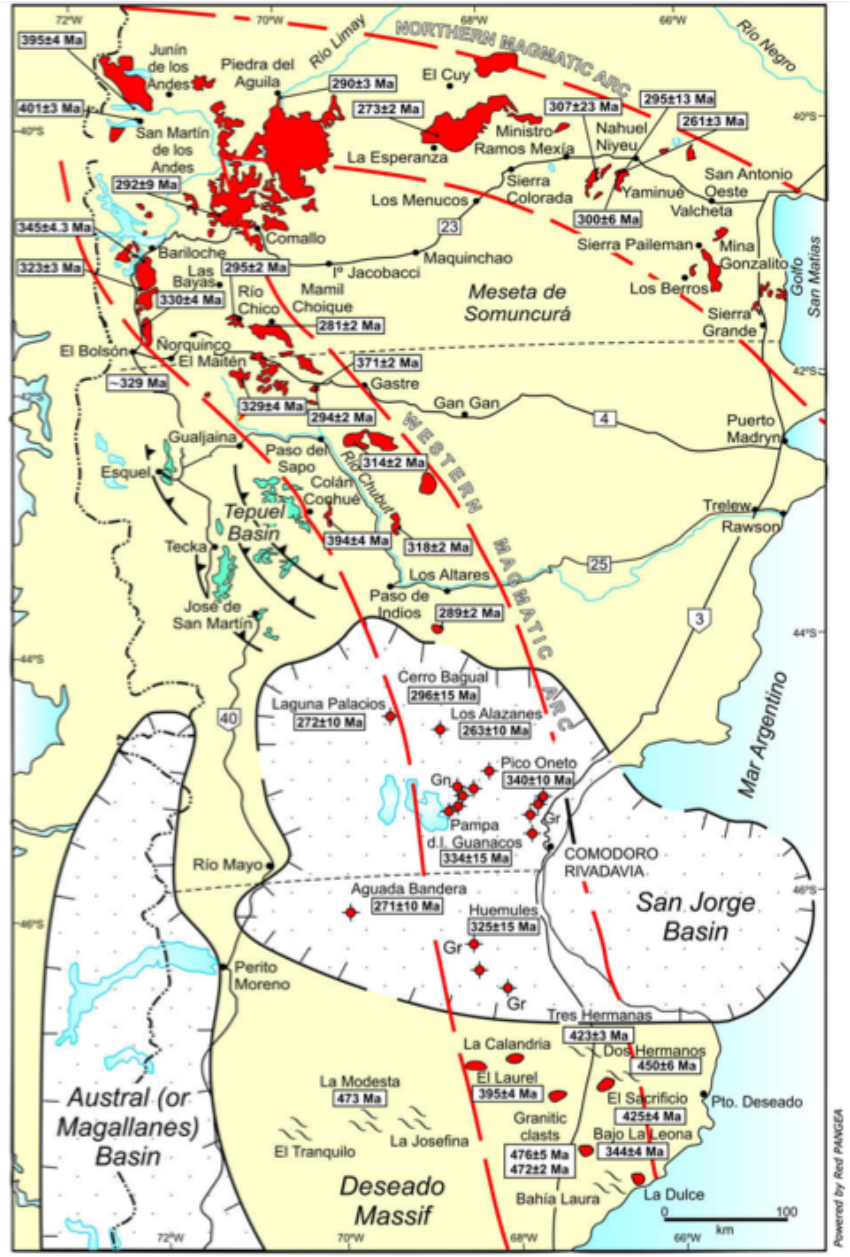


Fig. 5. Exposures of magmatic rocks of the northern and western belts of the Somún Cura Massif based on Cortiñas (1996), and extension of the western belt in the Deseado Massif. U–Pb ages in the northern belt are mainly based on Basei et al. (1999, 2005) and Varela et al. (1998a,b, 1999, 2005, 2007). The U–Pb ages in the western belt are mainly from Varela et al. (2005) and Pankhurst et al. (2003, 2006). The subsurface K–Ar ages from drilling cores are from Lesta et al. (1980), Linares and González (1990), and location of the wells from Sylwan (2001).

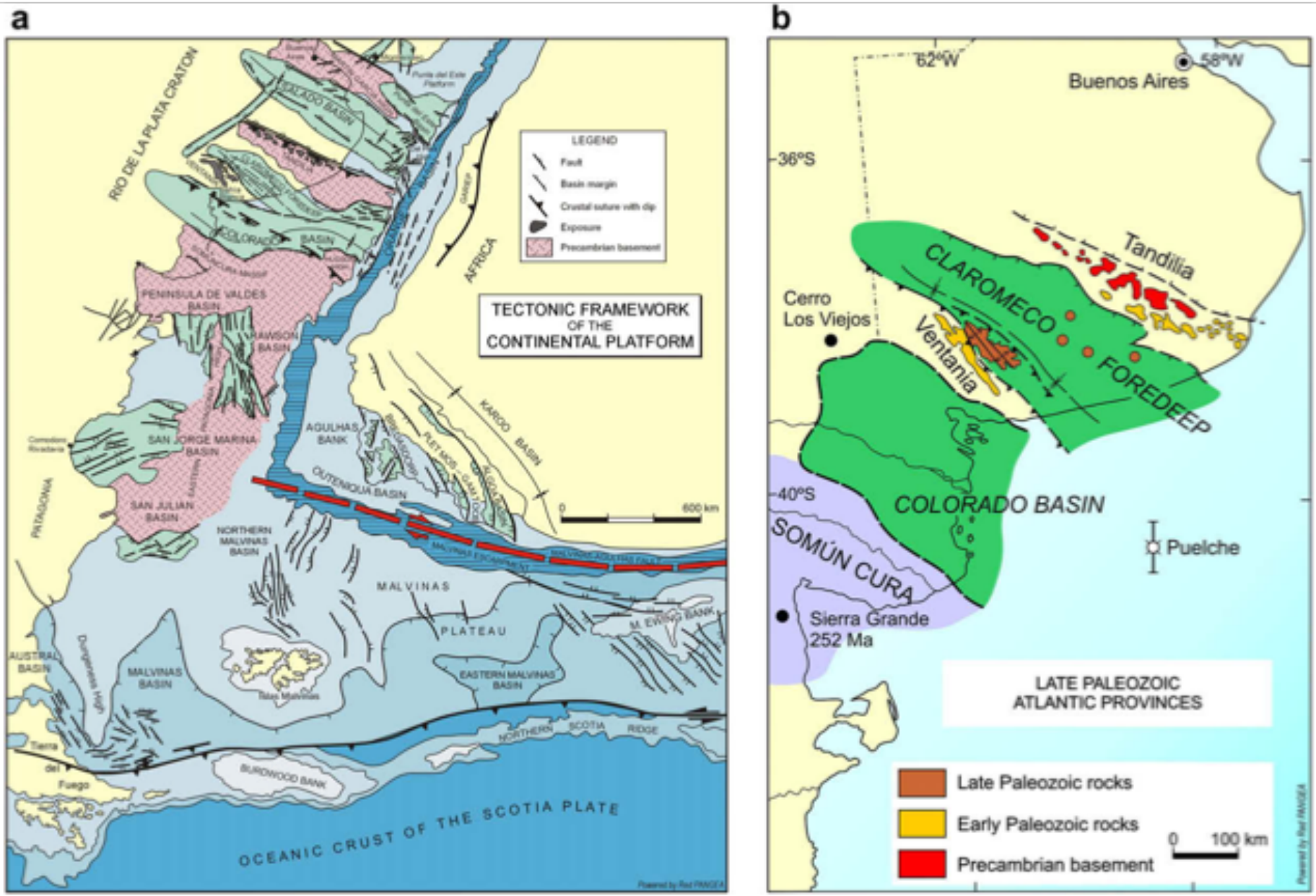
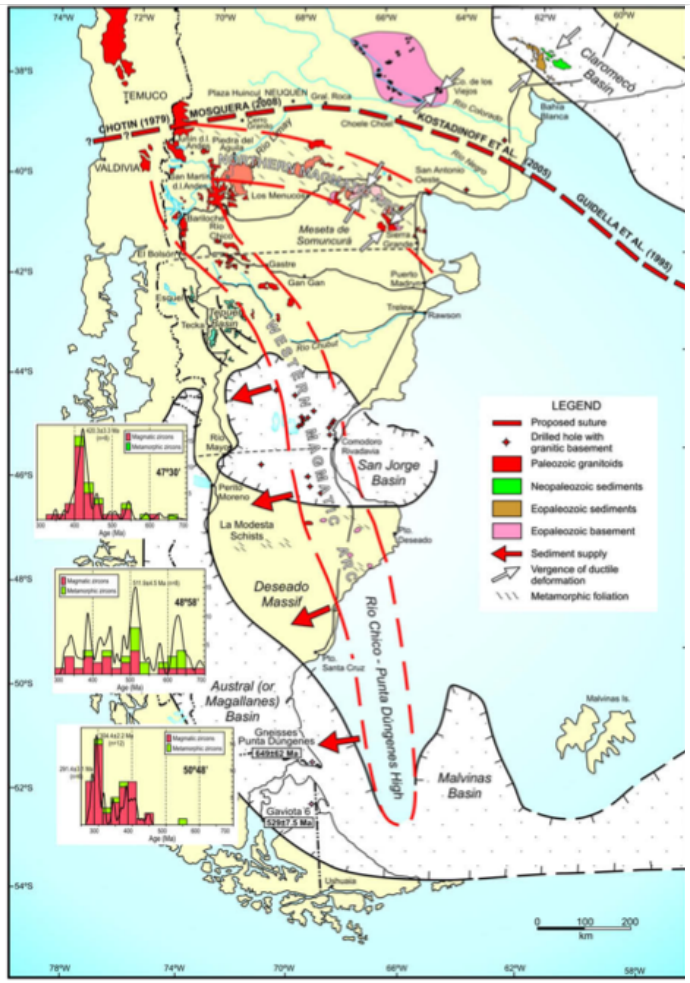
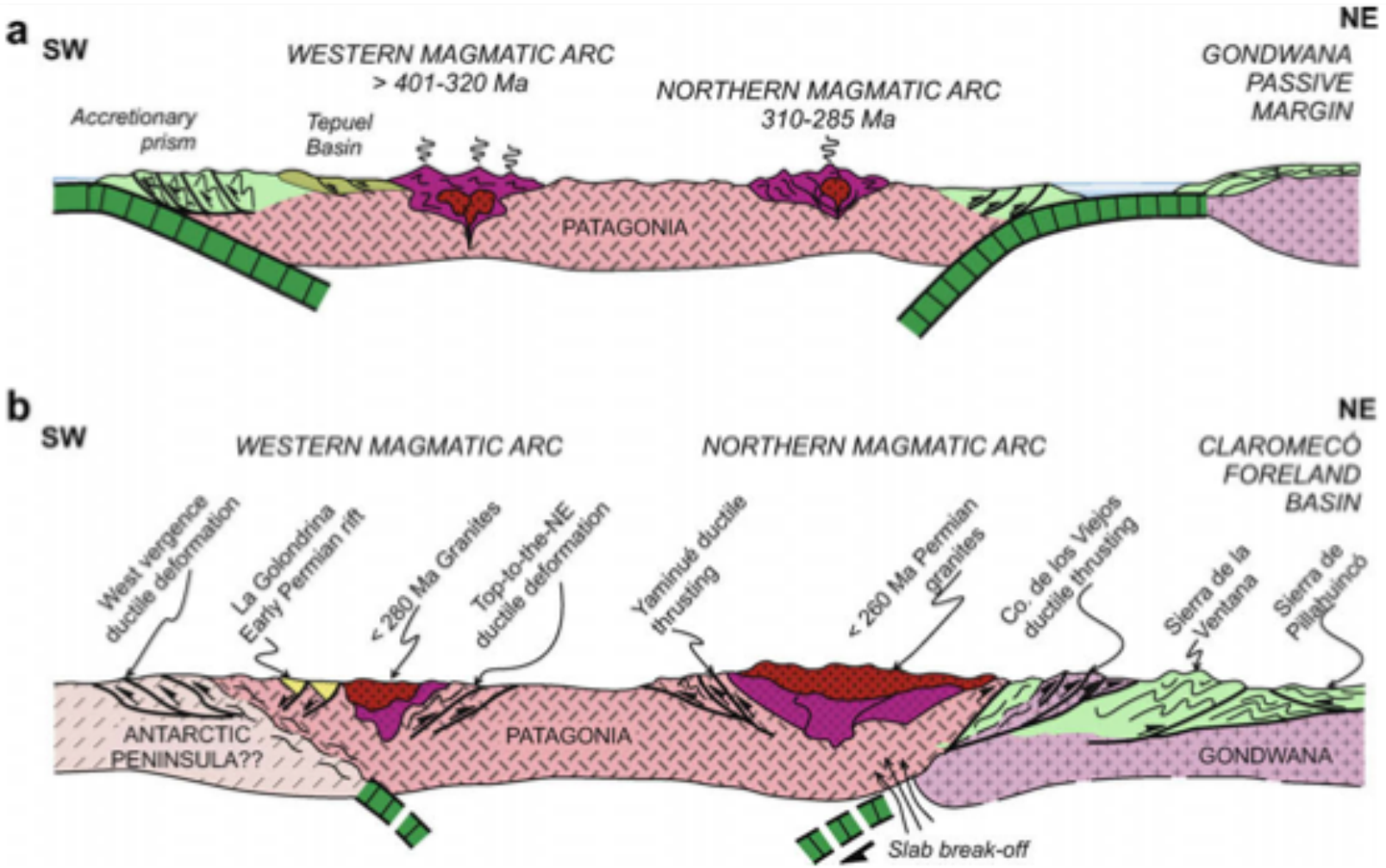


Fig. 9. (a) Structure of the continental platforms of southern South America and southern Africa based on the early fit of Martin et al. (1981) and complemented with new structural features by Ramos (1996); (b) Detail of the late Paleozoic provinces in the South America sides showing that the contact between the northern igneous and metamorphic belt of Somún Cura and the Claromecó foredeep is covered by the Late Jurassic–Cretaceous aulacogenic Colorado basin (De Wit, 1977).


TEMUCO
VALDIVIA
CHOTIN (1979)
MOSQUERA (2008)
KOSTADINOFF ET AL. (2005)
GUIDELLA ET AL. (1995)
Claromecó Basin
Mesets de Somuncurá
San Jorge Basin
Deseado Massif
Austral (or Magallanes) Basin
Malvinas Basin
Río Chico - Punta Dúngenes High
La Modesta Schists
Gneisses Punta Dúngenes
Gaviota 6
Malvinas Is.
LEGEND
Proposed suture
Drilled hole with granitic basement
Paleozoic granitoids
Neopaleozoic sediments
Eopaleozoic sediments
Eopaleozoic basement
Sediment supply
Vergence of ductile deformation
Metamorphic foliation
0 100 200 km


a
SW
NE
WESTERN MAGMATIC ARC
> 401-320 Ma
NORTHERN MAGMATIC ARC
310-285 Ma
GONDWANA PASSIVE MARGIN
Accretionary prism
Tepuel Basin
PATAGONIA
b
SW
NE
WESTERN MAGMATIC ARC
NORTHERN MAGMATIC ARC
CLAROMECÓ FORELAND BASIN
West vergence ductile deformation
La Golondrina Early Permian rift
< 280 Ma Granites
Top-to-the-NE ductile deformation
Yaminué ductile thrusting
< 260 Ma Permian granites
Co. de los Viejos ductile thrusting
Sierra de la Ventana
Sierra de Pillahuincó
ANTARCTIC PENINSULA??
PATAGONIA
GONDWANA
Slab break-off

Estudo dirigido, Origem e evolução da Patagônia (com base em Ramos, 2008).

1) Descreva as principais feições da Geologia da Patagônia, seus principais maciços e bacias.

2) Quais os intervalos de idade dos cinturões magmáticos e metamórficos que cortam a porção norte e central da Patagônia?

3) Qual o limite norte da Patagônia. Quais os argumentos de Ramos (2008) para definir este limite?

4) A Patagônia tem uma ou duas suturas? Onde estas suturas estariam localizadas?

5) A Patagônia é um terreno alóctone? Se sim, quando a Patagônia teria sido integrada ao restante do Gondwana? Há evidência paleomagnética para esta hipótese?