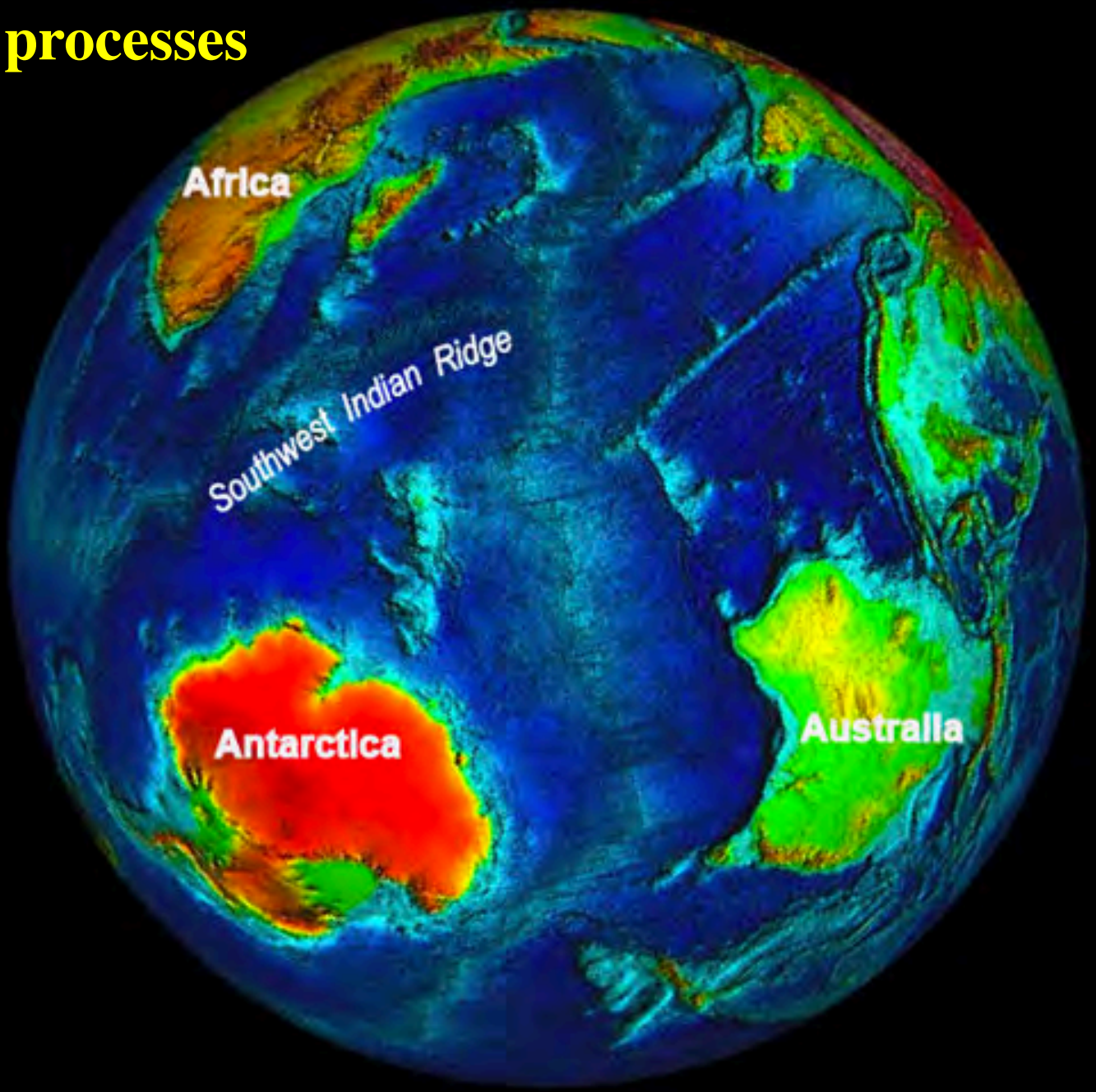
Theme 4:Geological and deep-ocean biogeochemical processes

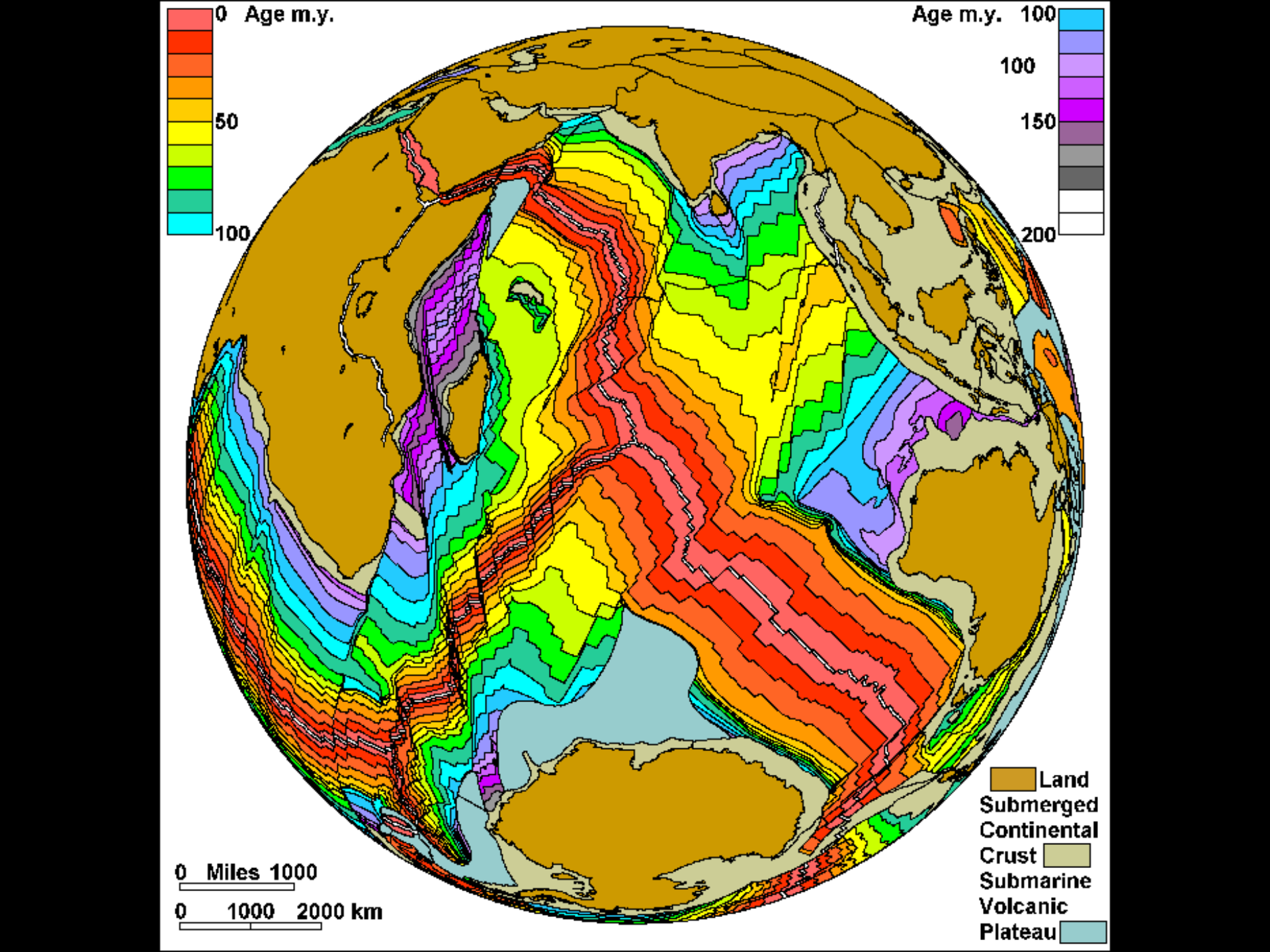
Part 1
Marine geology
&
Geophysics

Henry Dick

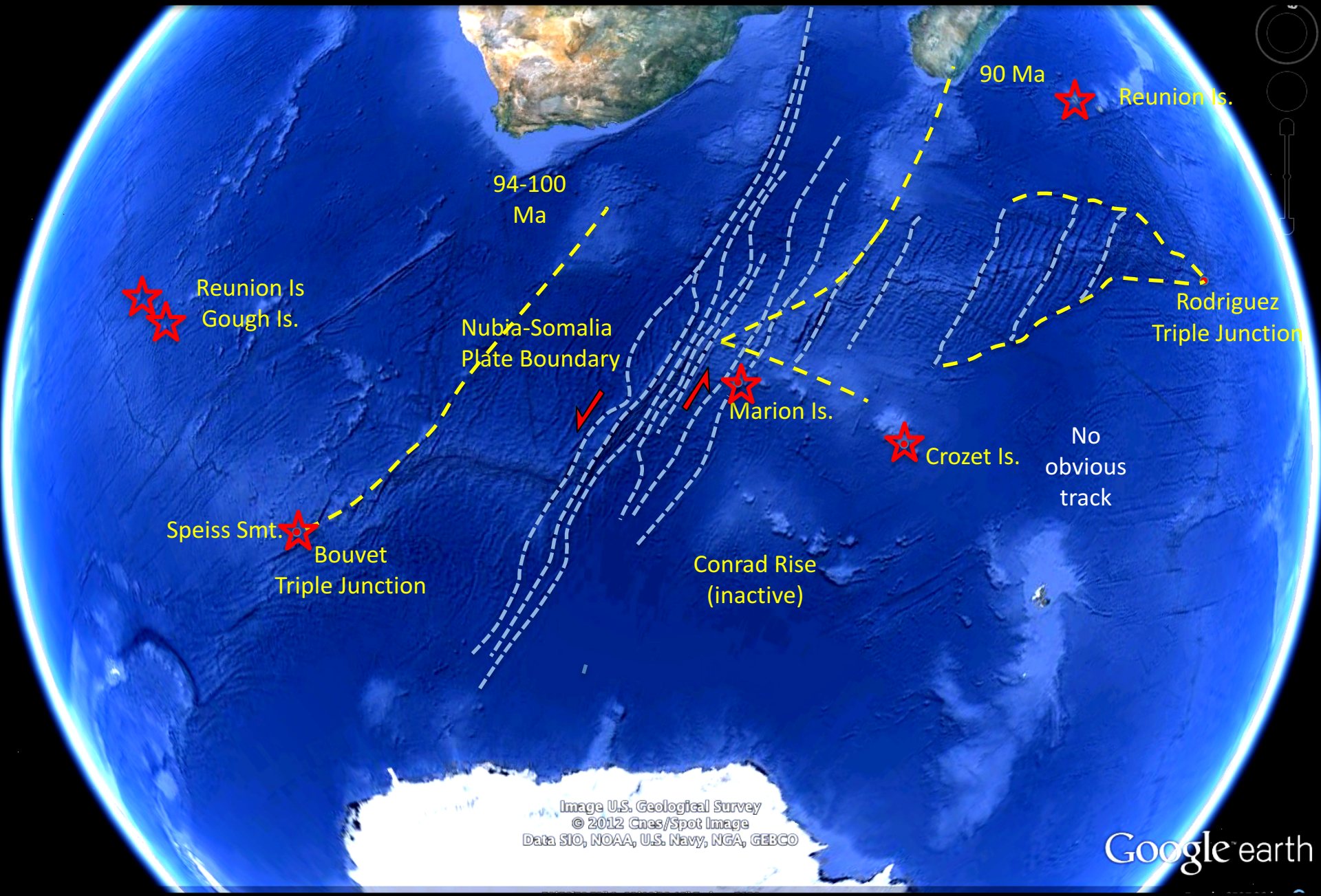
WHOI

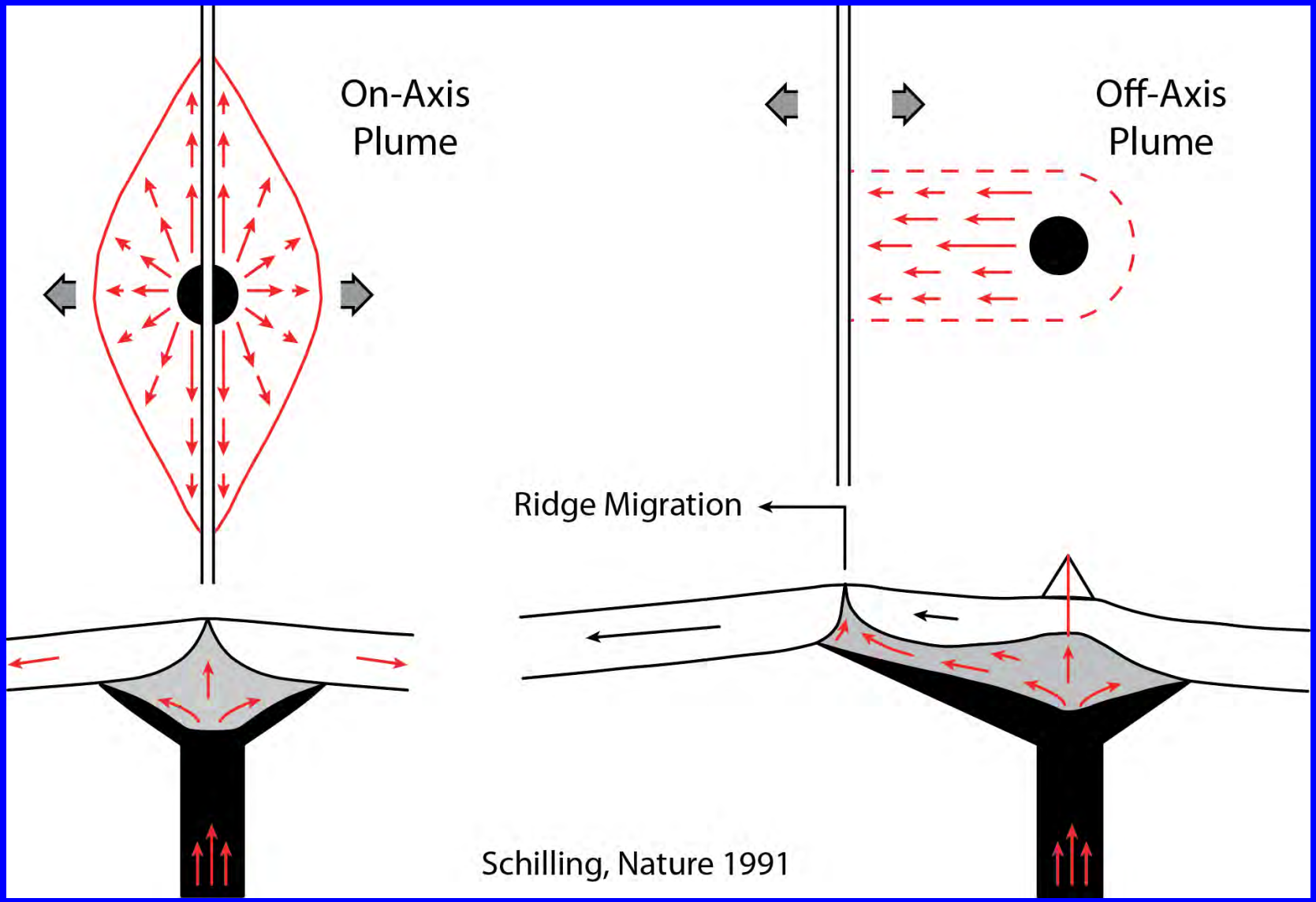


IIOE-2
2nd International
Indian Ocean
Expedition

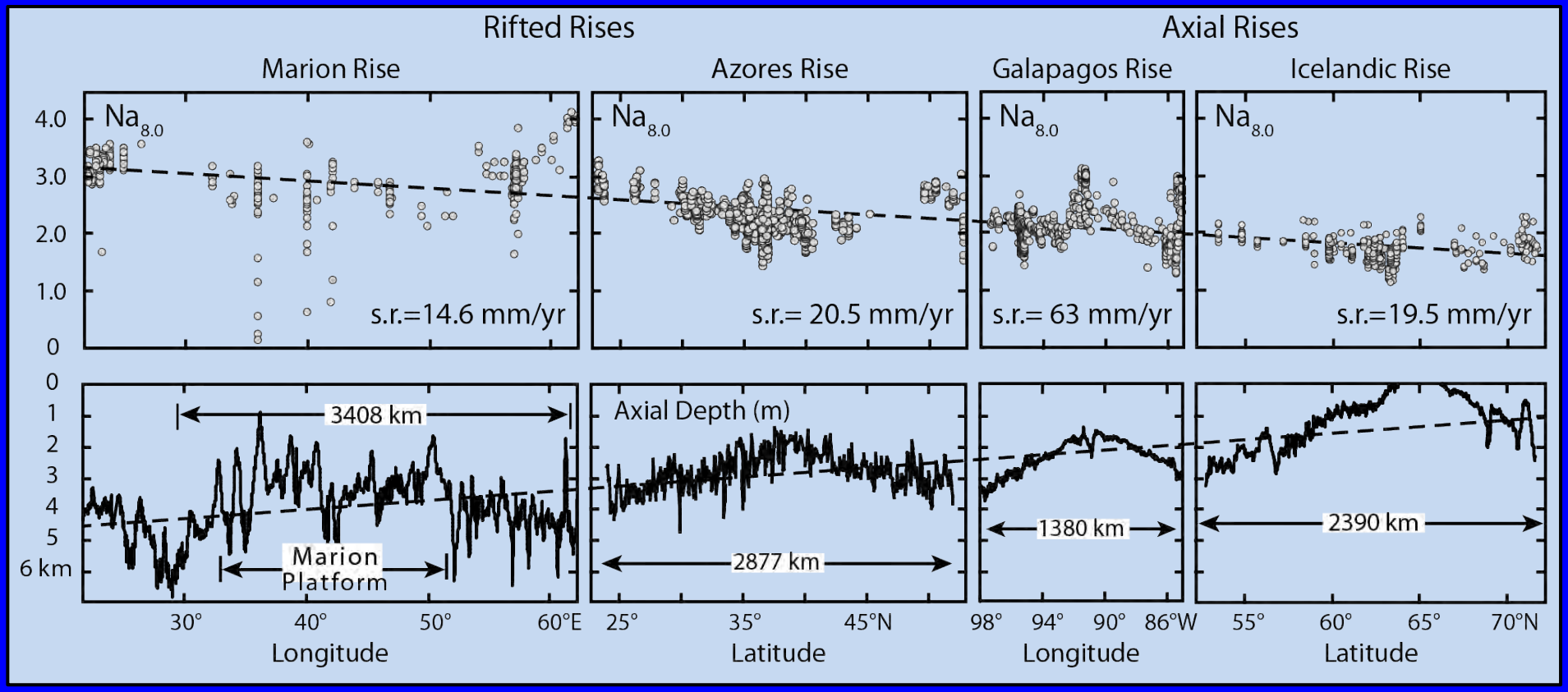

0 Age m.y.
50
100
Age m.y. 100
100
150
200
0 Miles 1000
0 1000 2000 km
Land
Submerged Continental Crust
Submarine Volcanic Plateau

The SW Indian Ridge – 7,700 km long, ultraslow spreading @ 14 mm/yr full rate





The general hypothesis for ocean rises is plume mantle emplaced beneath the ridge creates uplift due to thick buoyant crust and excess mantle temperature



Cold? → Hot?

Marion Rise has the highest $Na_{8.0}$ of all ocean rises, which indicates that the degree of mantle melting must be small & the temperature anomaly associated with it must also be small.

Depleted? → Fertile?

The Southwest Indian Ridge

Largest abundance of exposed mantle rock anywhere on Earth

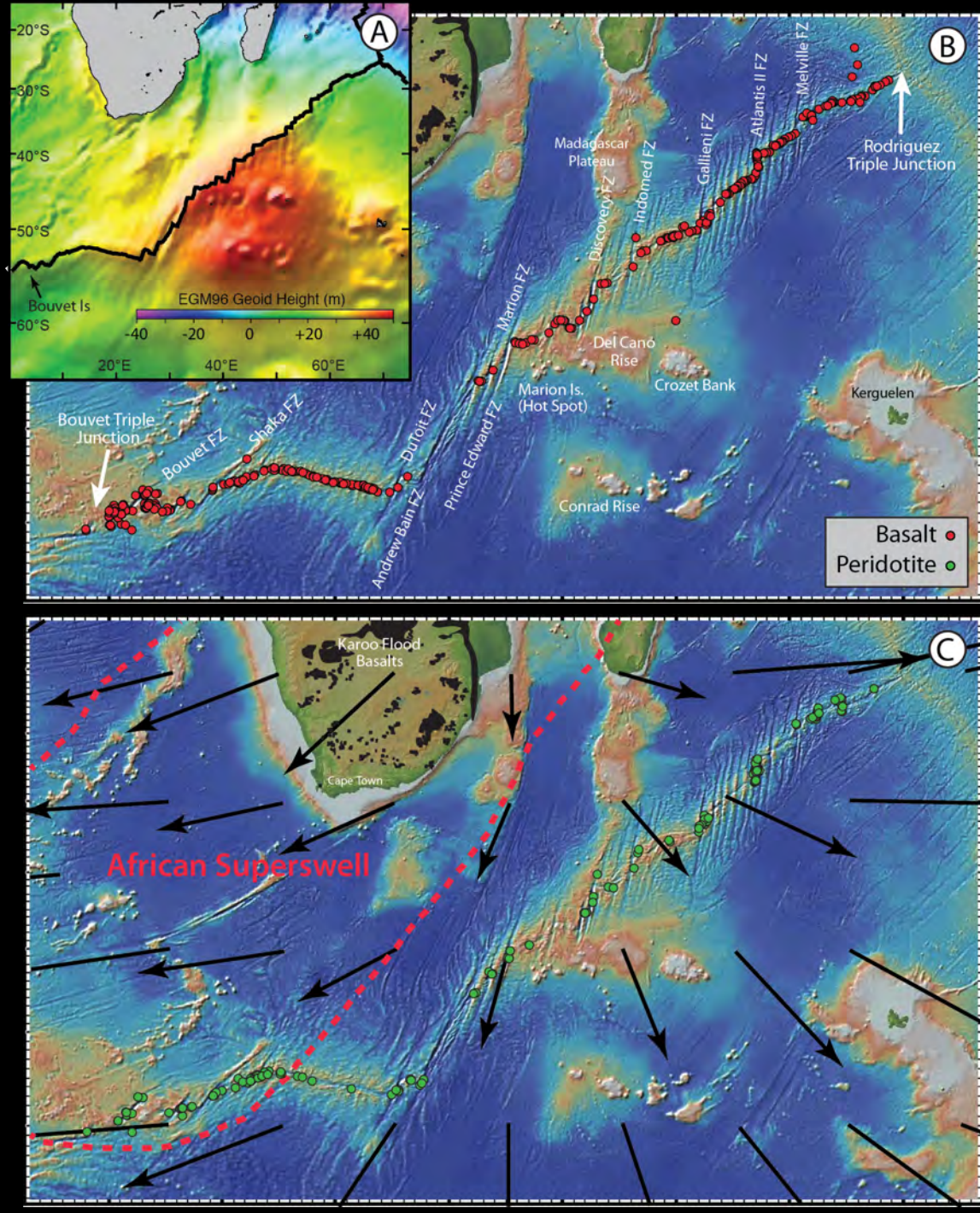
Ultraslow spreading with unique tectonics

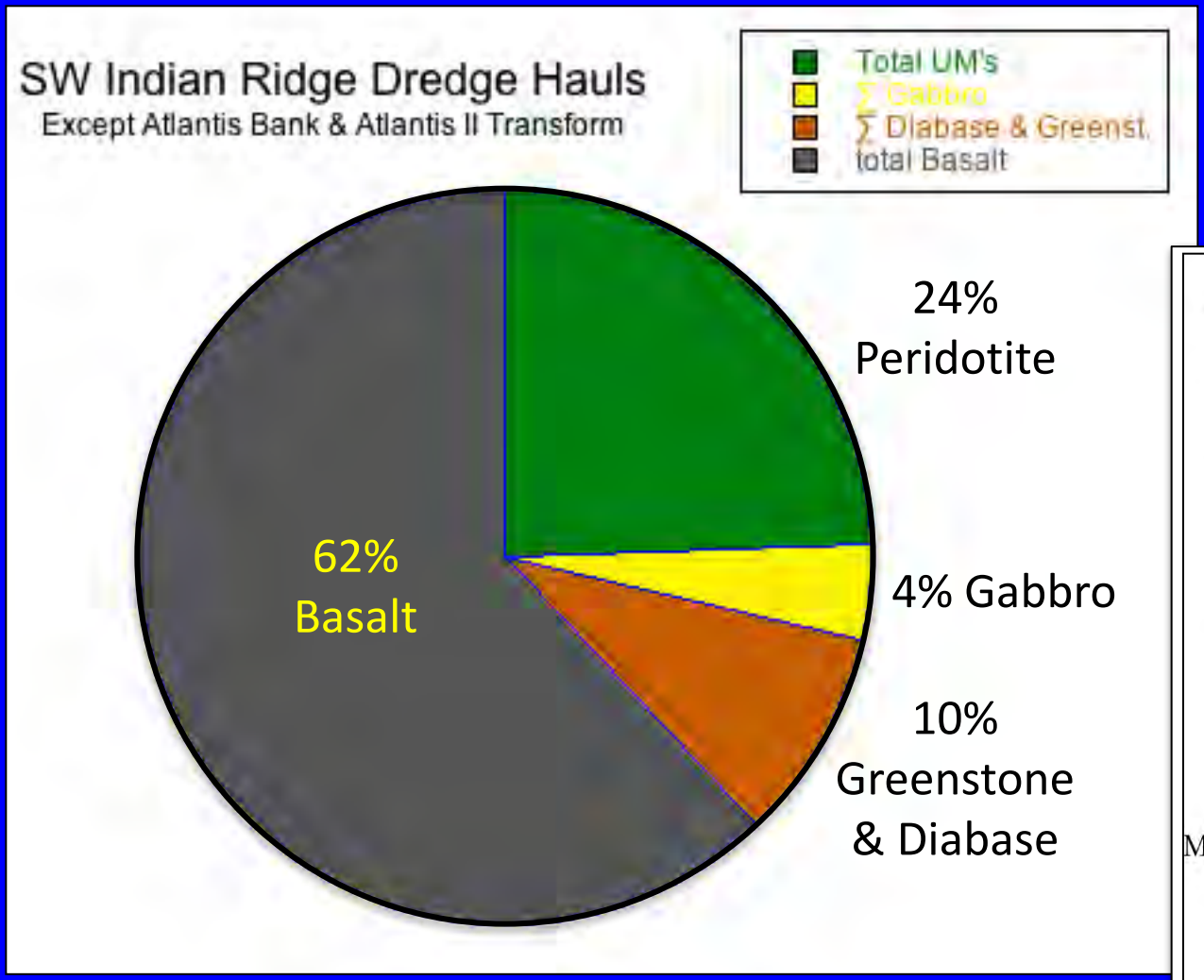
Largest axial volcanoes on any ocean ridge

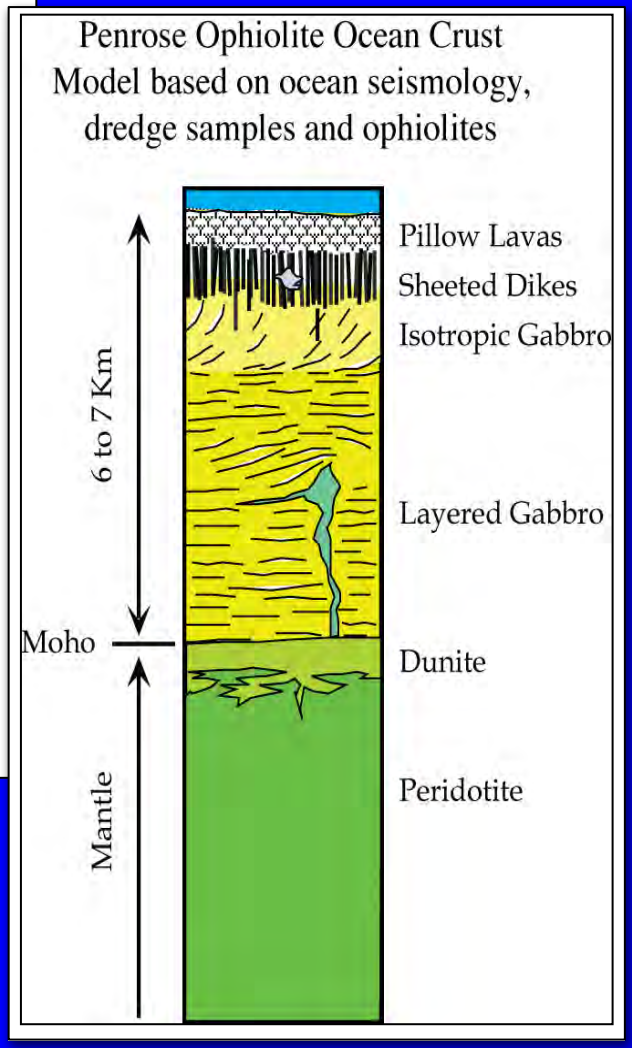
Extreme ridge obliquity creates unusual thermal environments

Densest array of transforms of any ocean ridge.

Has one of the oldest continuously active geologic structures on Earth (~650 Myr)

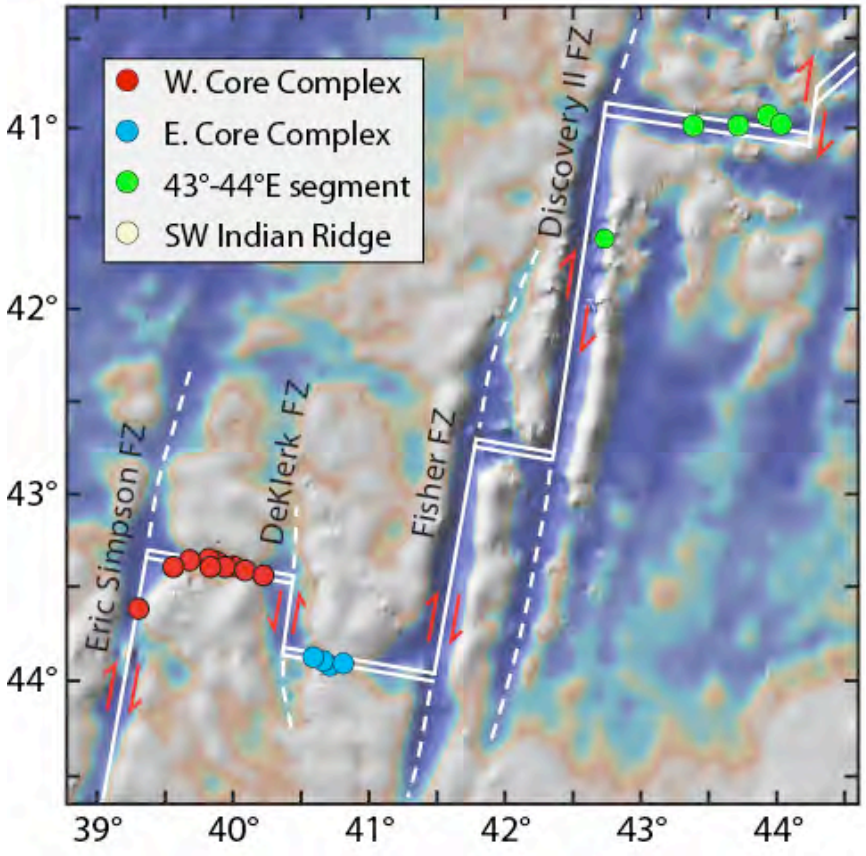


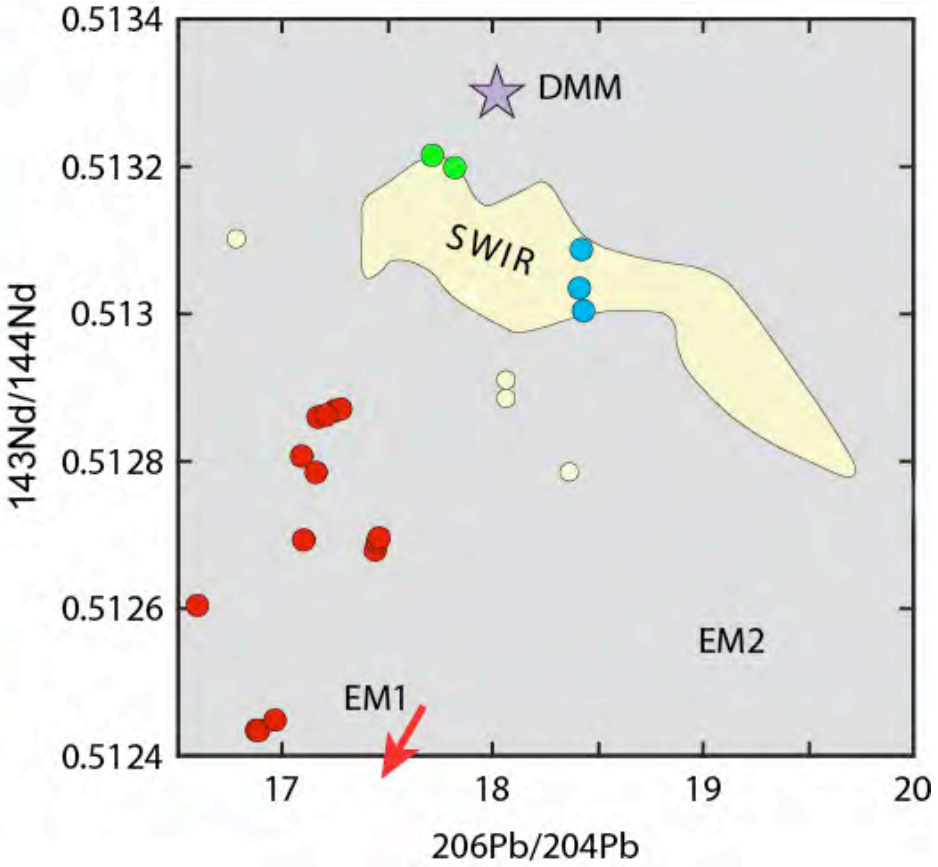




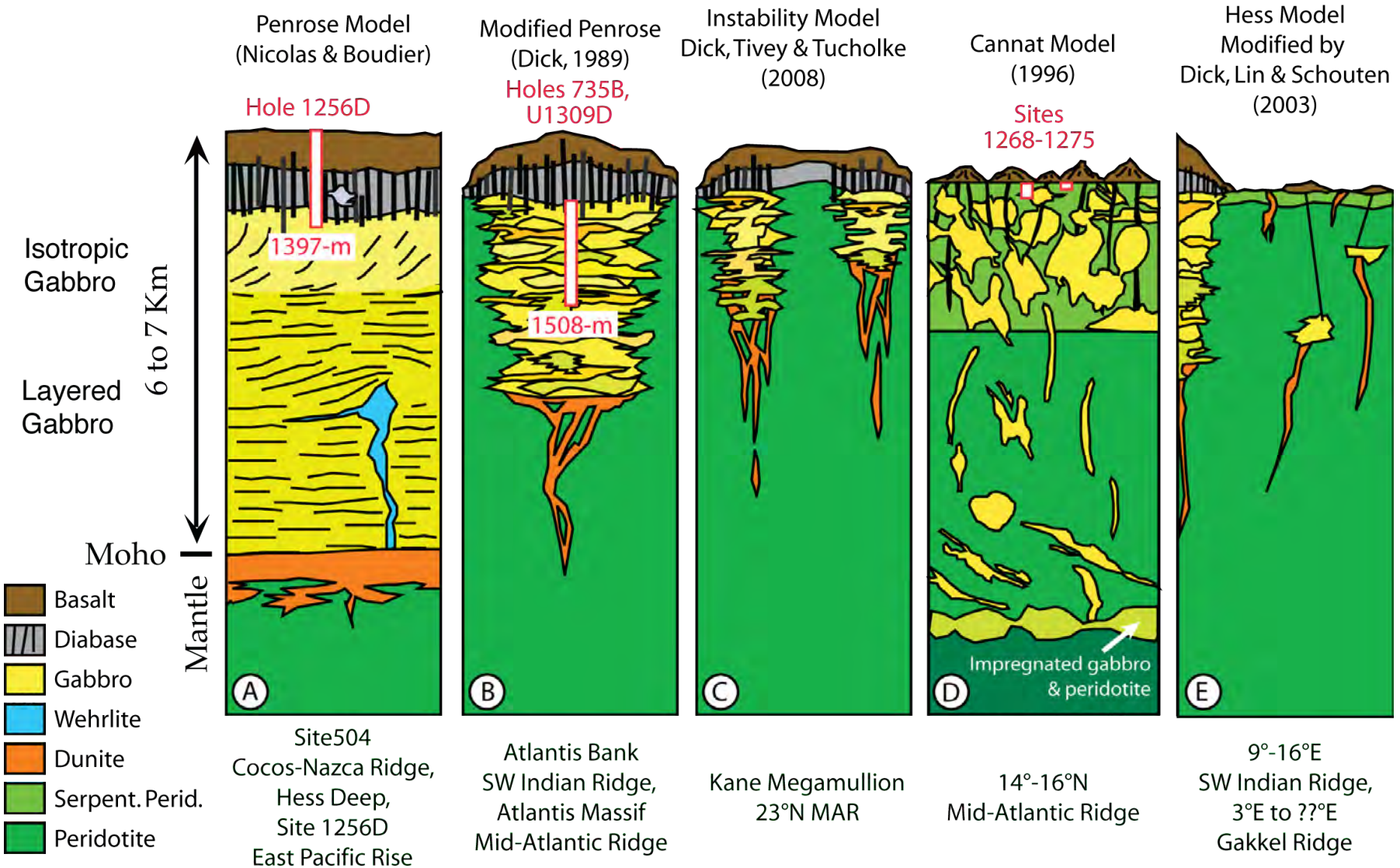
Systematic sampling of the SW Indian Ridge shows a lack of gabbroic crust and an exceptional % of exposed mantle

Extreme variations in crustal thickness are matched by extreme variations in geochemistry





Ocean Ridge Crustal Accretion Models

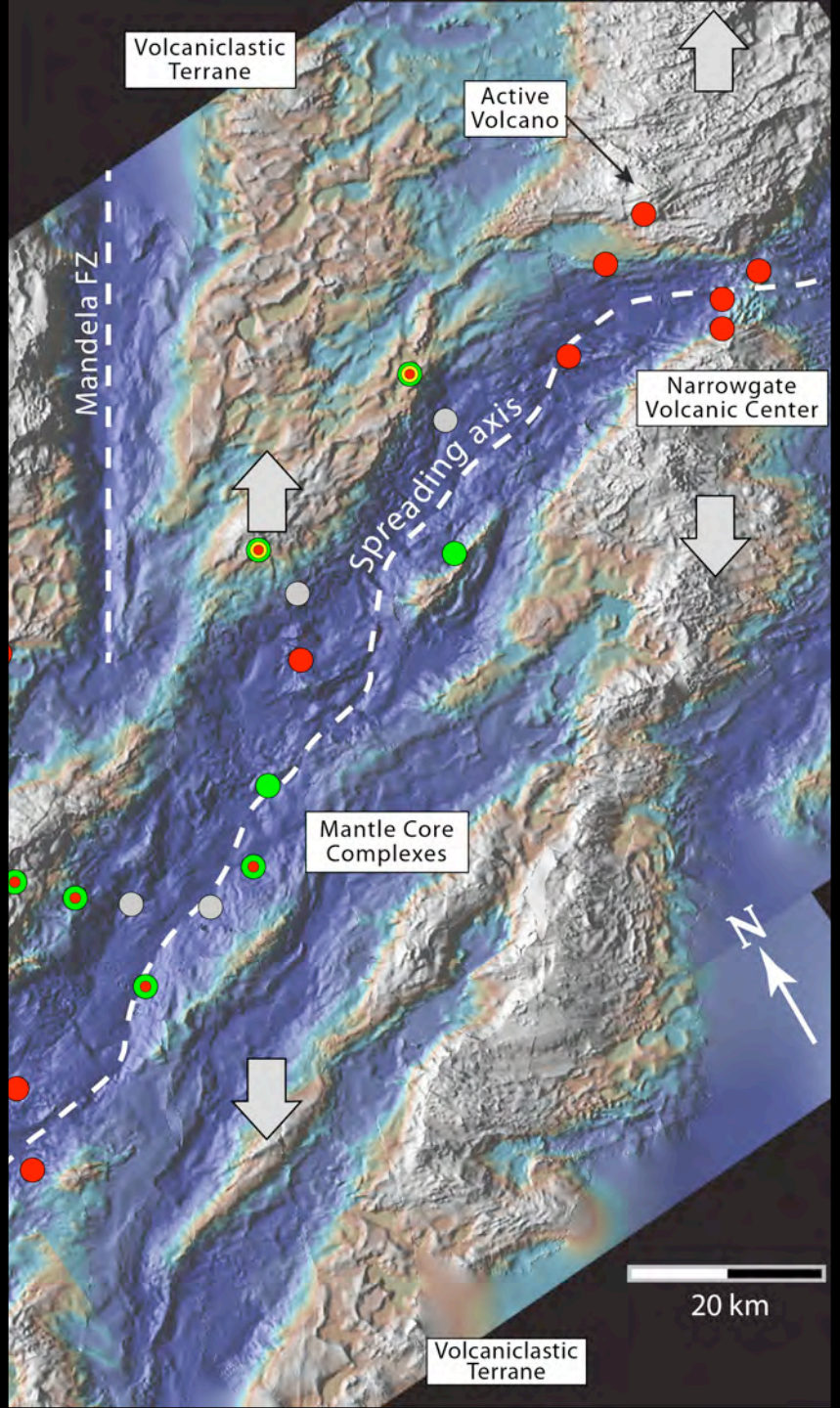


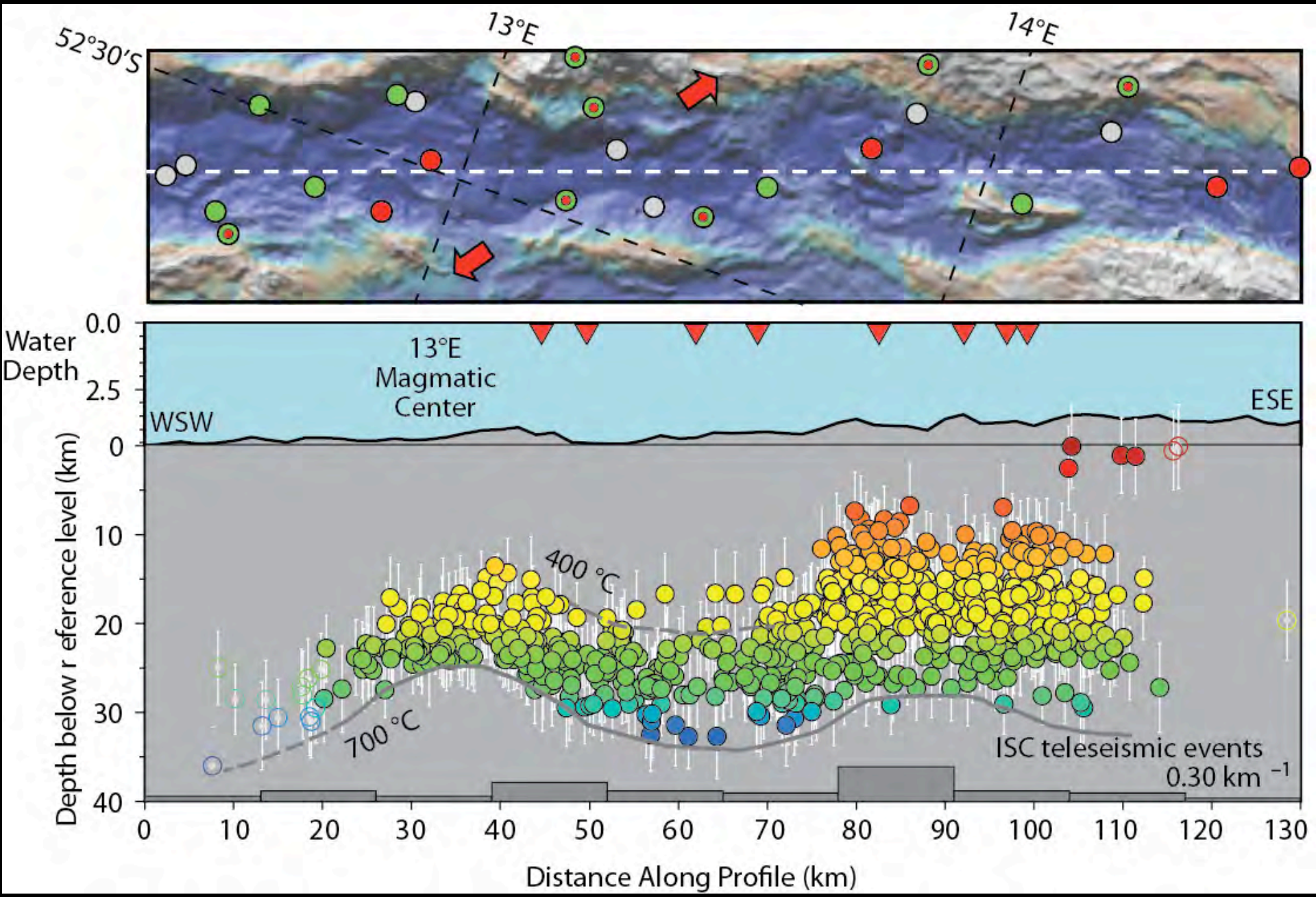
Amagmatic Accretionary Segments

Negligible Volcanic Crust

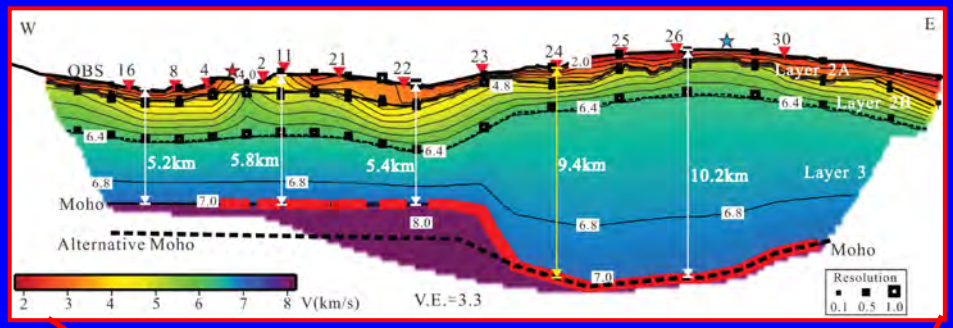
Takes any Orientation to Spreading Direction

~24% of the lithosphere generated along the Southwest Indian Ridge has no crust with the mantle exposed directly to the seafloor.



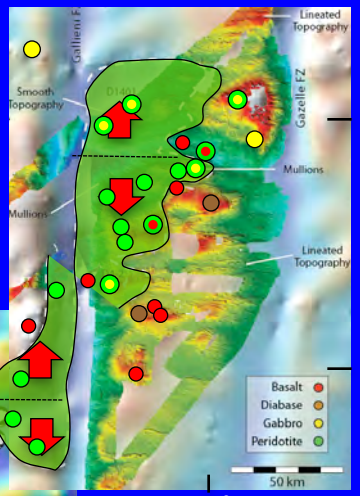

52°30'S
13°E
14°E
Water Depth
0.0
2.5
0
13°E
Magmatic
Center
WSW
ESE
10
20
30
40
400 °C
700 °C
ISC teleseismic events
0.30 km −1
Depth below r eference level (km)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Distance Along Profile (km)

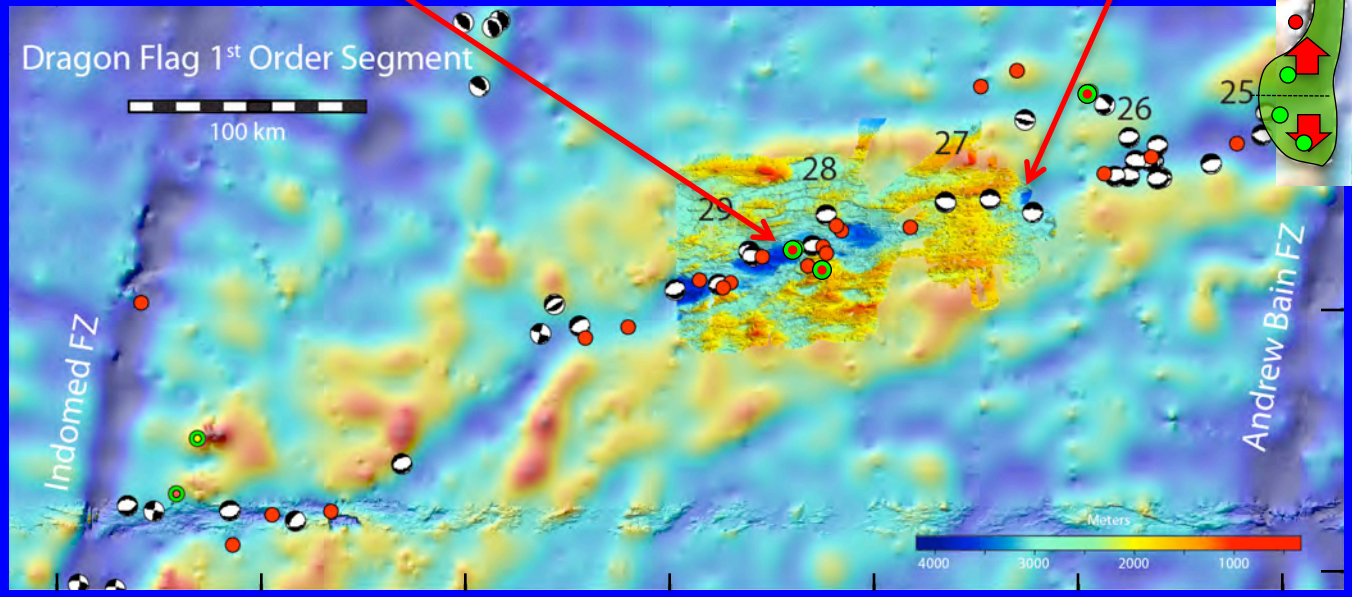
The crust over the Marion Rise and elsewhere along the is generally thin, but with abrupt rapid changes in local thickness. For example, from 50° E to 52° E, <100 km it goes from 10-km thick to zero thickness.



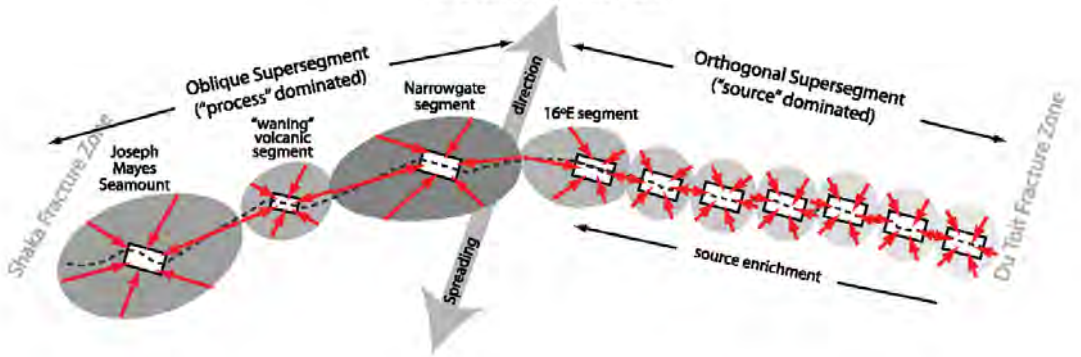
10-km crust

Zero crust

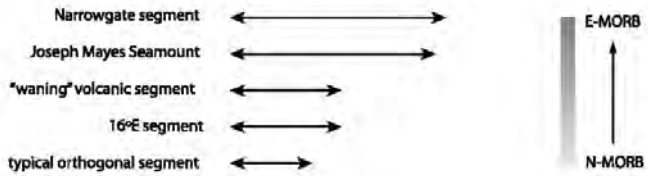


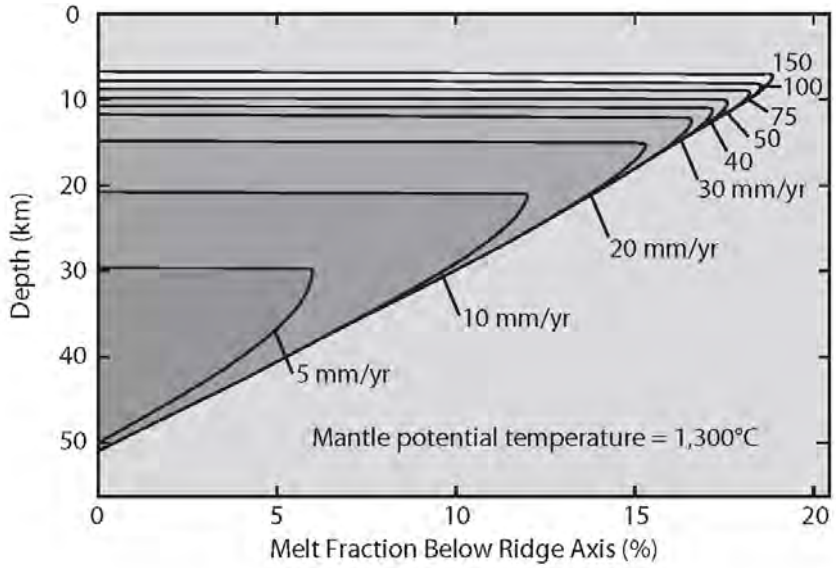


Segmentation and Melt Generation Regions
"Effective Segmentation"

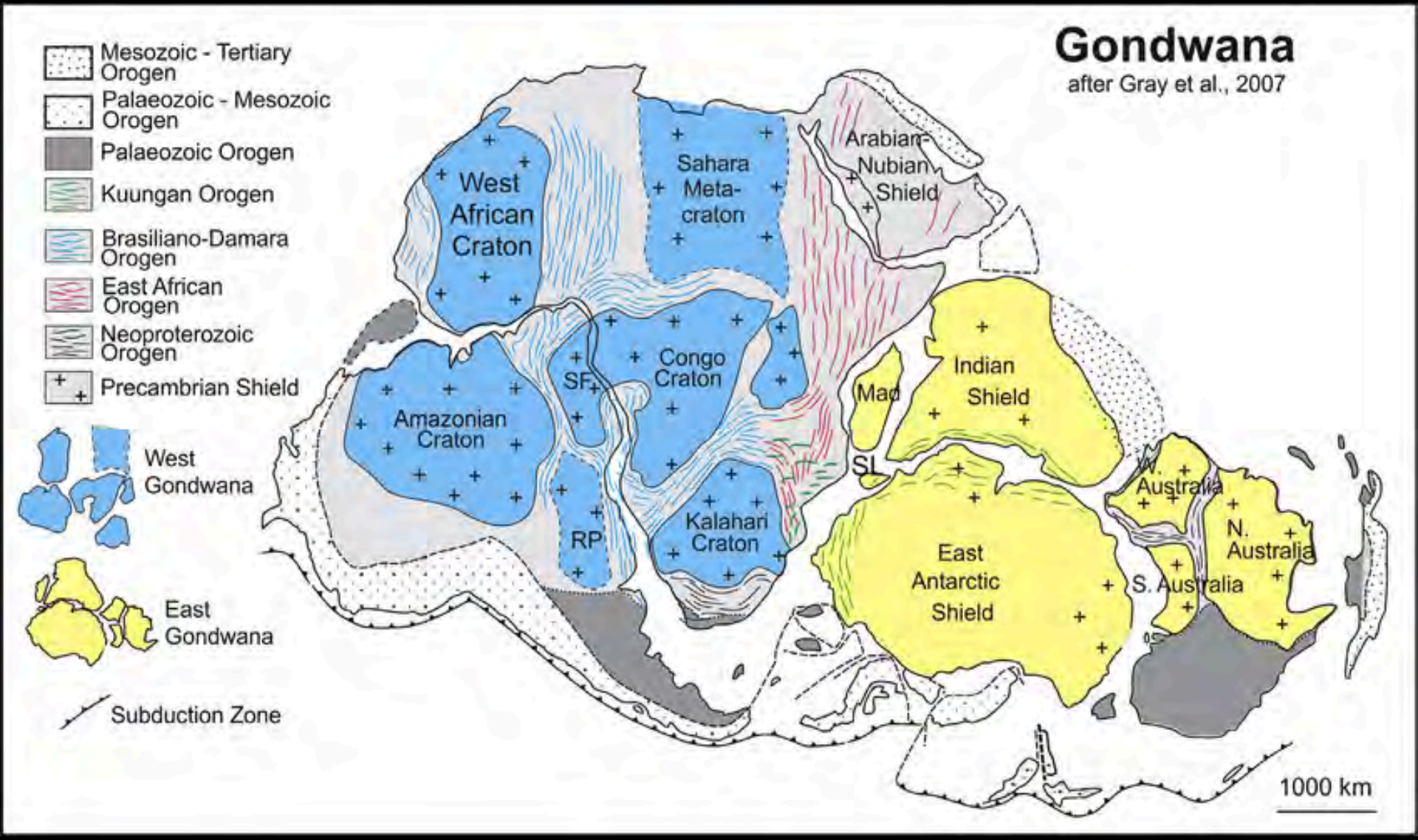


Relative Length-Scales for Melt Generation Regions

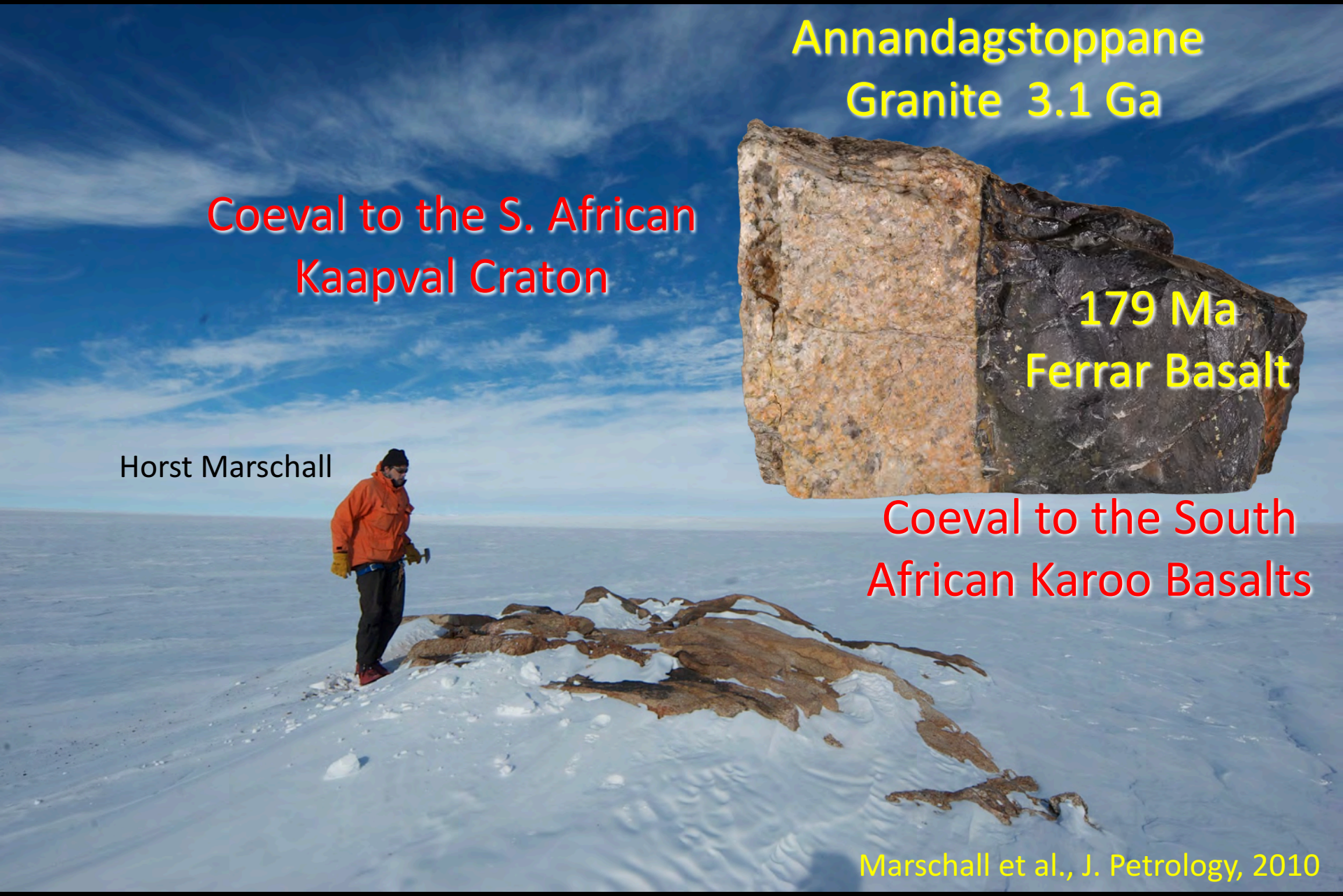




18.9% @ 150 mm/yr
16.6% @ 30
13.7% @ 20
12.0% @ 10

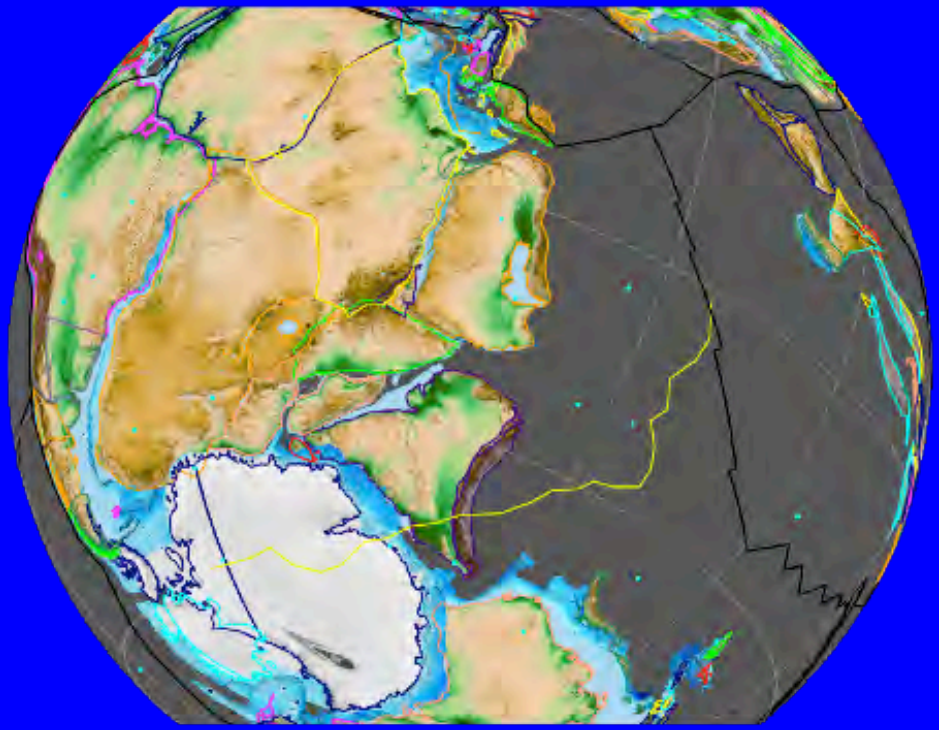

Gondwana
after Gray et al., 2007
Mesozoic - Tertiary Orogen
Palaeozoic - Mesozoic Orogen
Palaeozoic Orogen
Kuungan Orogen
Brasiliano-Damara Orogen
East African Orogen
Neoproterozoic Orogen
Precambrian Shield
West Gondwana
East Gondwana
Subduction Zone
West African Craton
Sahara Meta-craton
Arabian-Nubian Shield
Amazonian Craton
SF
Congo Craton
Mad
Indian Shield
SL
RP
Kalahari Craton
East Antarctic Shield
W. Australia
N. Australia
S. Australia
1000 km

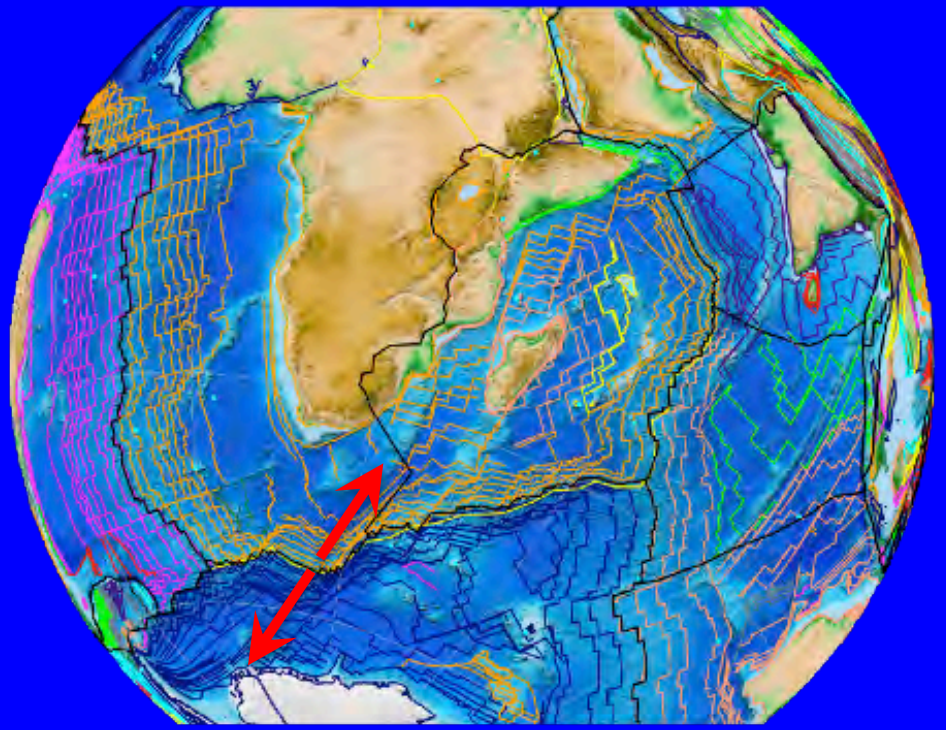

MEGA LAURASIA
Cimmerian Orogen
Shigatze
Ocean
Dras Arc
IC
NEOTETHYS
AFRICA
ZANSKAR
INDIA
E. Gondwana
ANTARCTICA
Tropic
Equator
Tropic
160
130


Annandagstoppane
Granite 3.1 Ga
Coeval to the S. African
Kaapval Craton
179 Ma
Ferrar Basalt
Horst Marschall
Coeval to the South
African Karoo Basalts
Marschall et al., J. Petrology, 2010

200 Ma

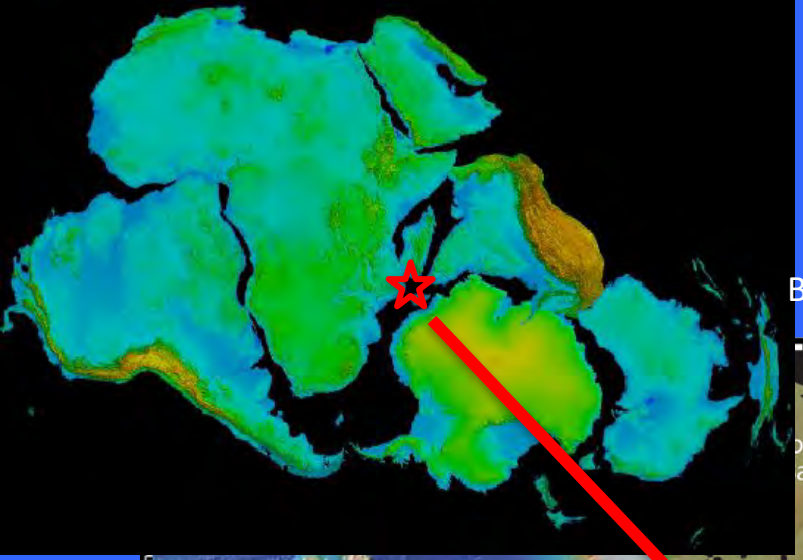
Today



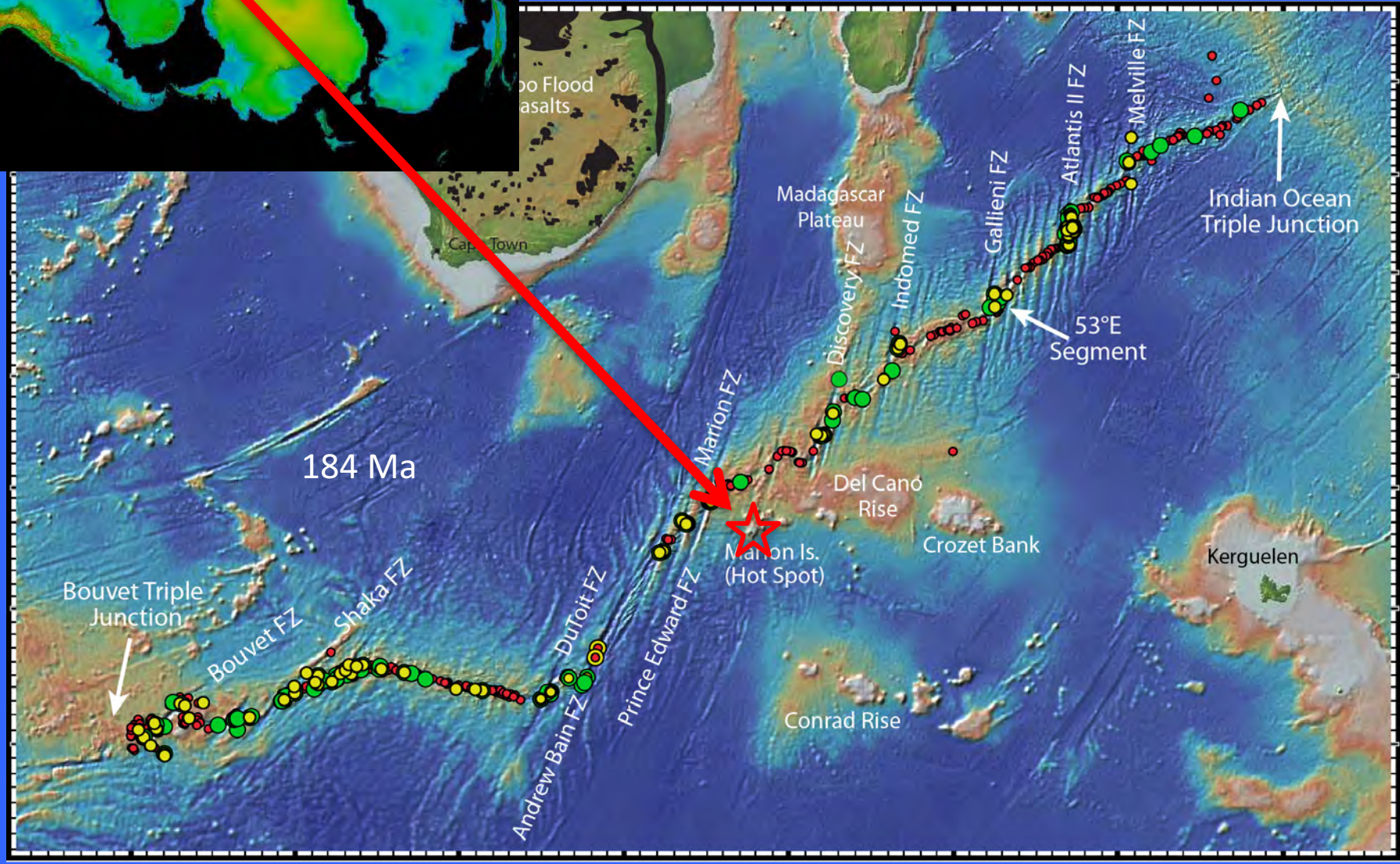


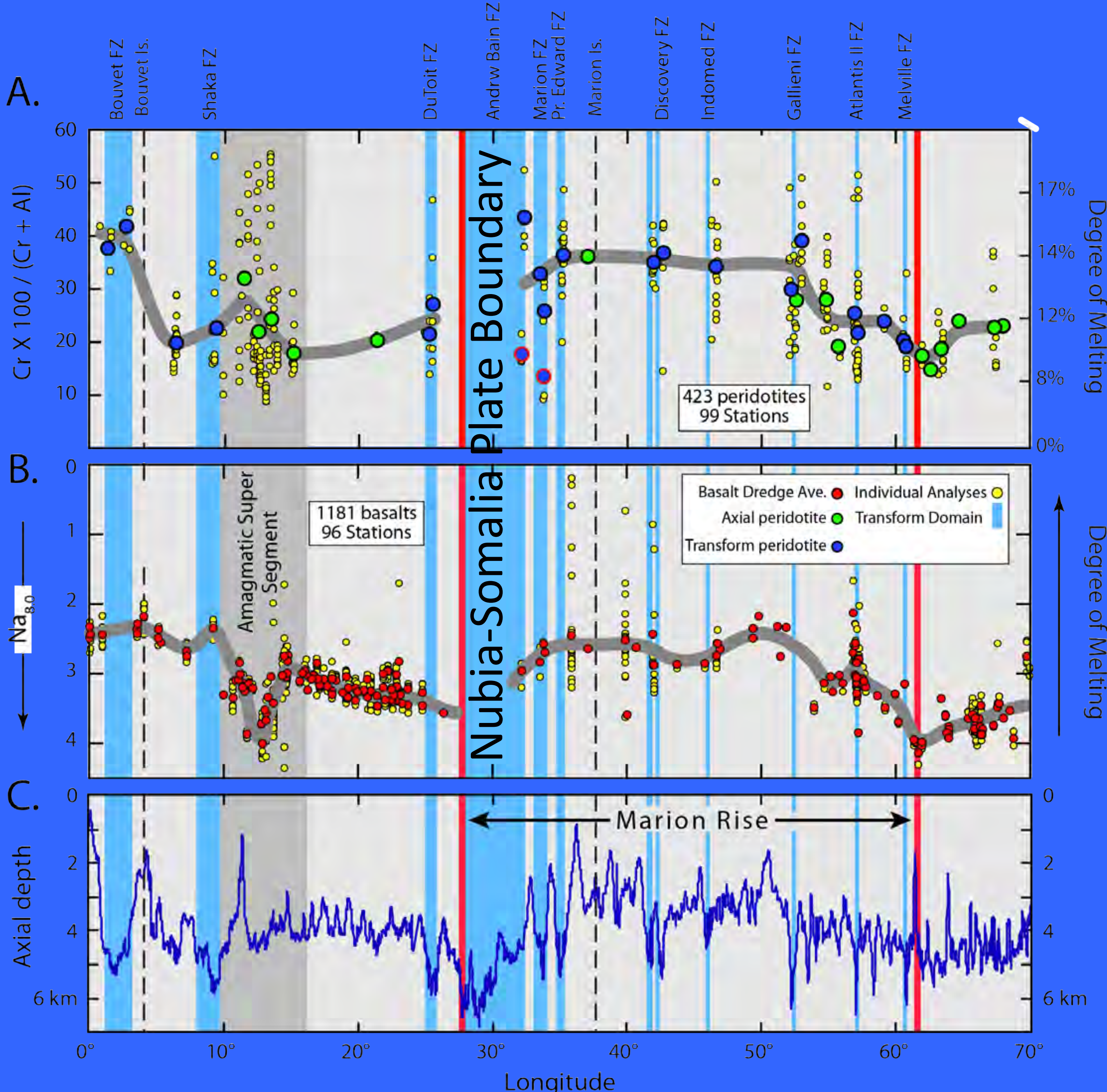
Initially the mantle that filled in between Africa and Antarctica had to be Gondwana's Mantle – the question is to what extent does it contribute to the mantle source of the SW Indian Ridge today?

Marion's paleo-position was the epicenter of Gondwanan breakup

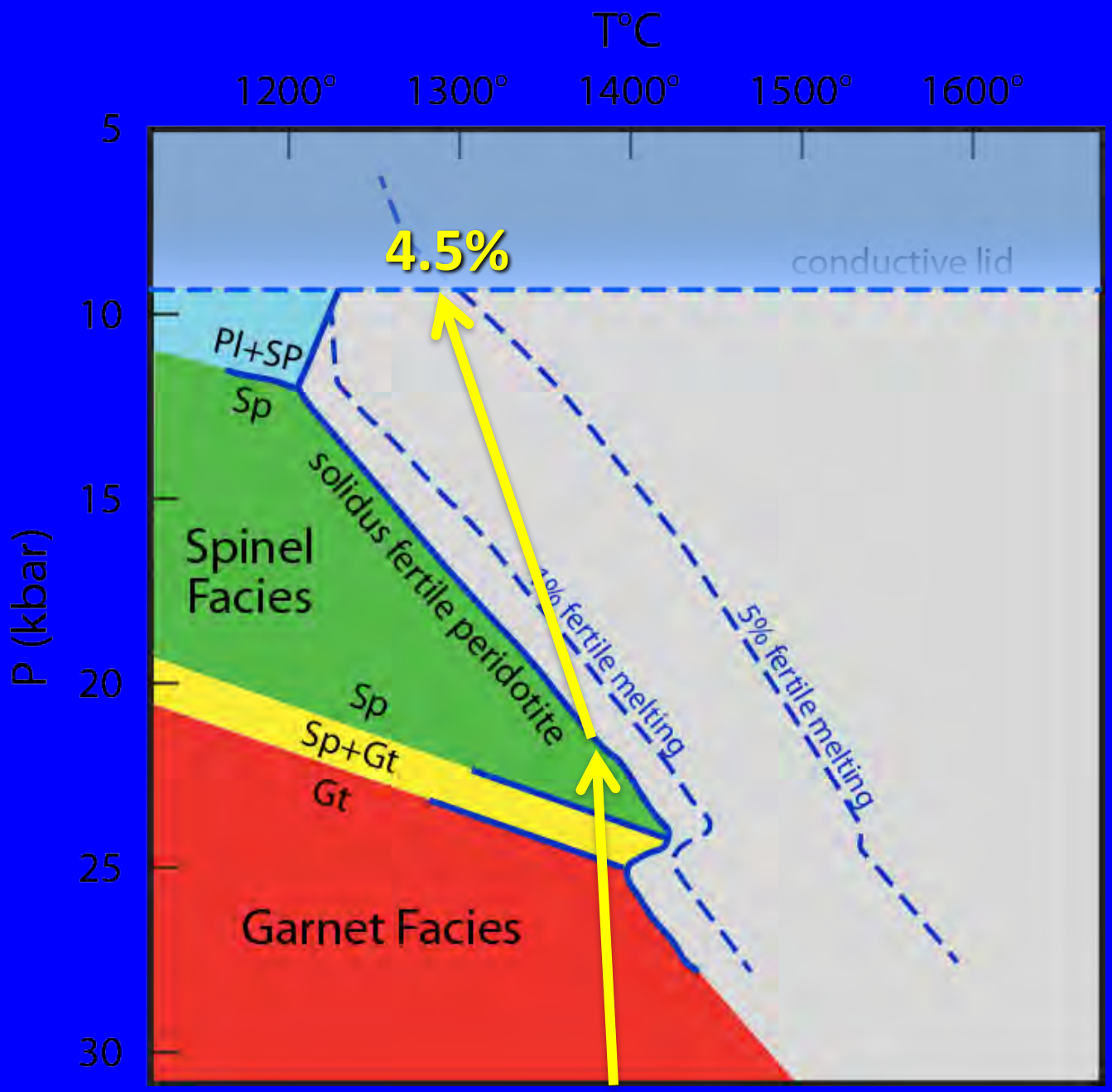


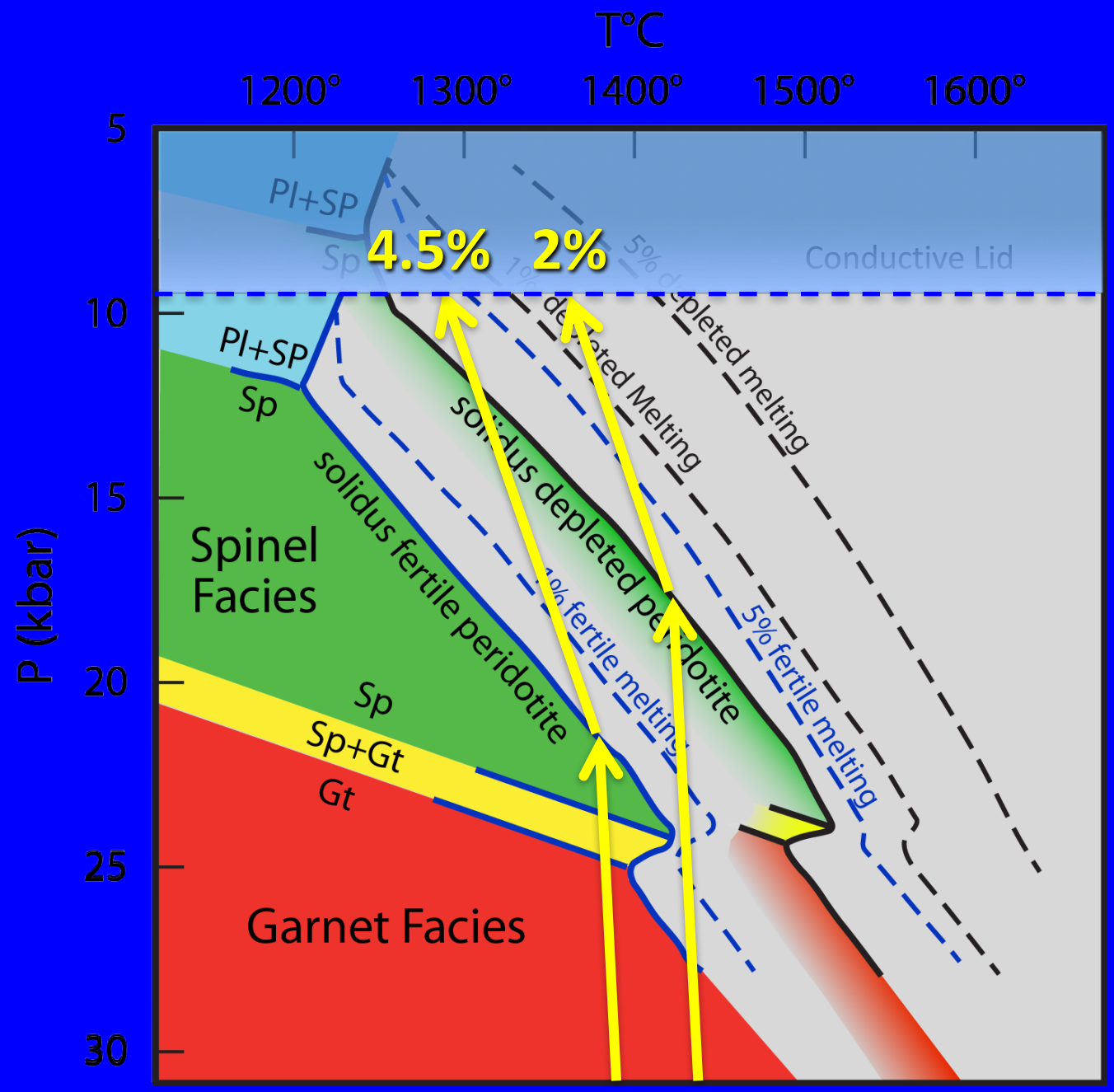
Basalt Gabbro Peridotite





A.
B.
C.
Bouvet FZ
Bouvet Is.
Shaka FZ
DuToit FZ
Andrw Bain FZ
Marion FZ
Pr. Edward FZ
Marion Is.
Discovery FZ
Indomed FZ
Gallieni FZ
Atlantis II FZ
Melville FZ
Cr X 100 / (Cr + Al)
Degree of Melting
17%
14%
12%
8%
0%
423 peridotites
99 Stations
Nubia-Somalia Plate Boundary
Amagmatic Super Segment
1181 basalts
96 Stations
Basalt Dredge Ave.
Individual Analyses
Axial peridotite
Transform Domain
Transform peridotite
$Na_{8.0}$
Marion Rise
Axial depth
6 km
Longitude
0°
10°
20°
30°
40°
50°
60°
70°


T°C
1200°
1300°
1400°
1500°
1600°
5
10
15
20
25
30
P (kbar)
4.5%
conductive lid
Pl+Sp
Sp
solidus fertile peridotite
Spinel Facies
% fertile melting
5% fertile melting
Sp
Sp+Gt
Gt
Garnet Facies

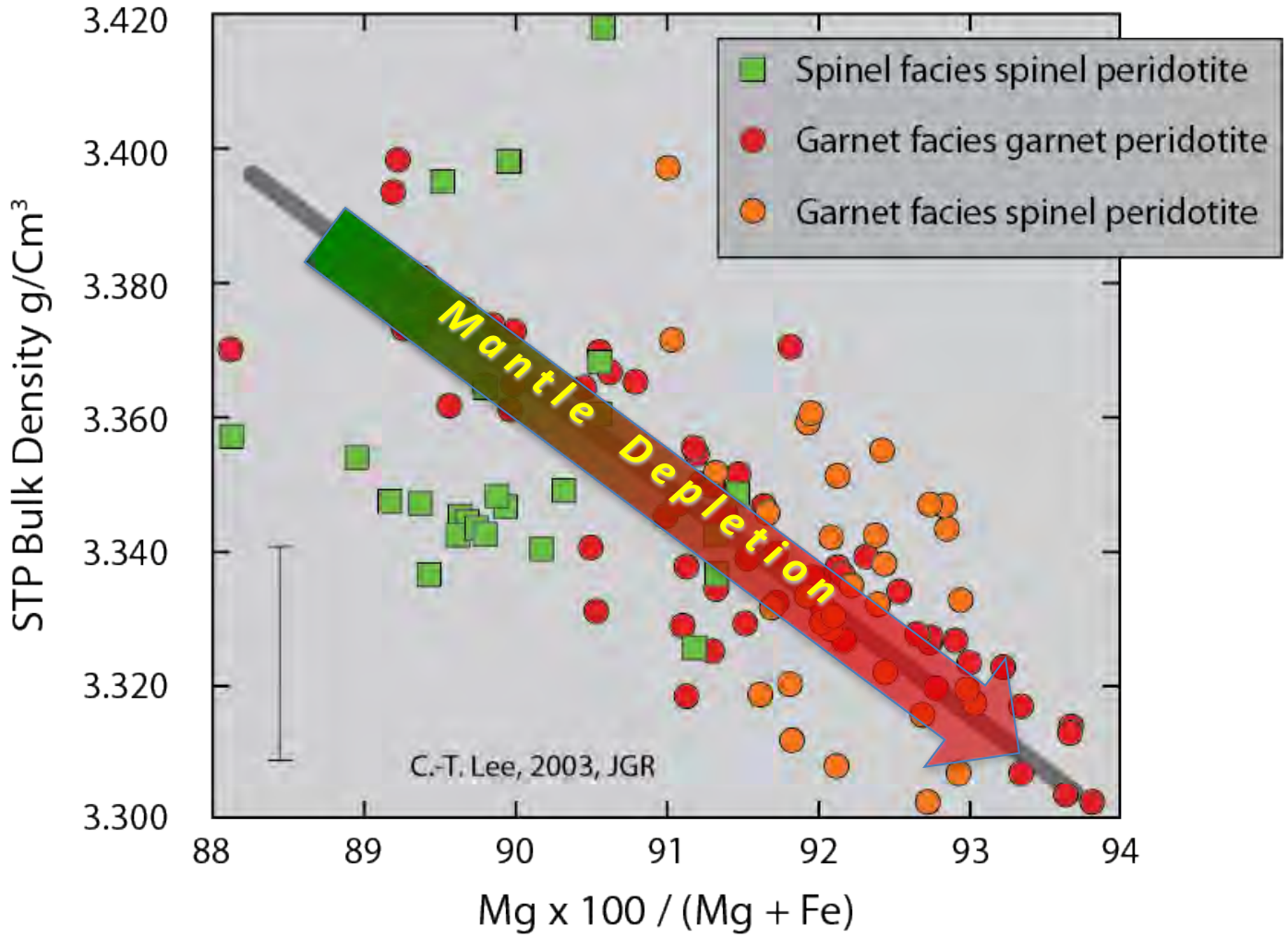


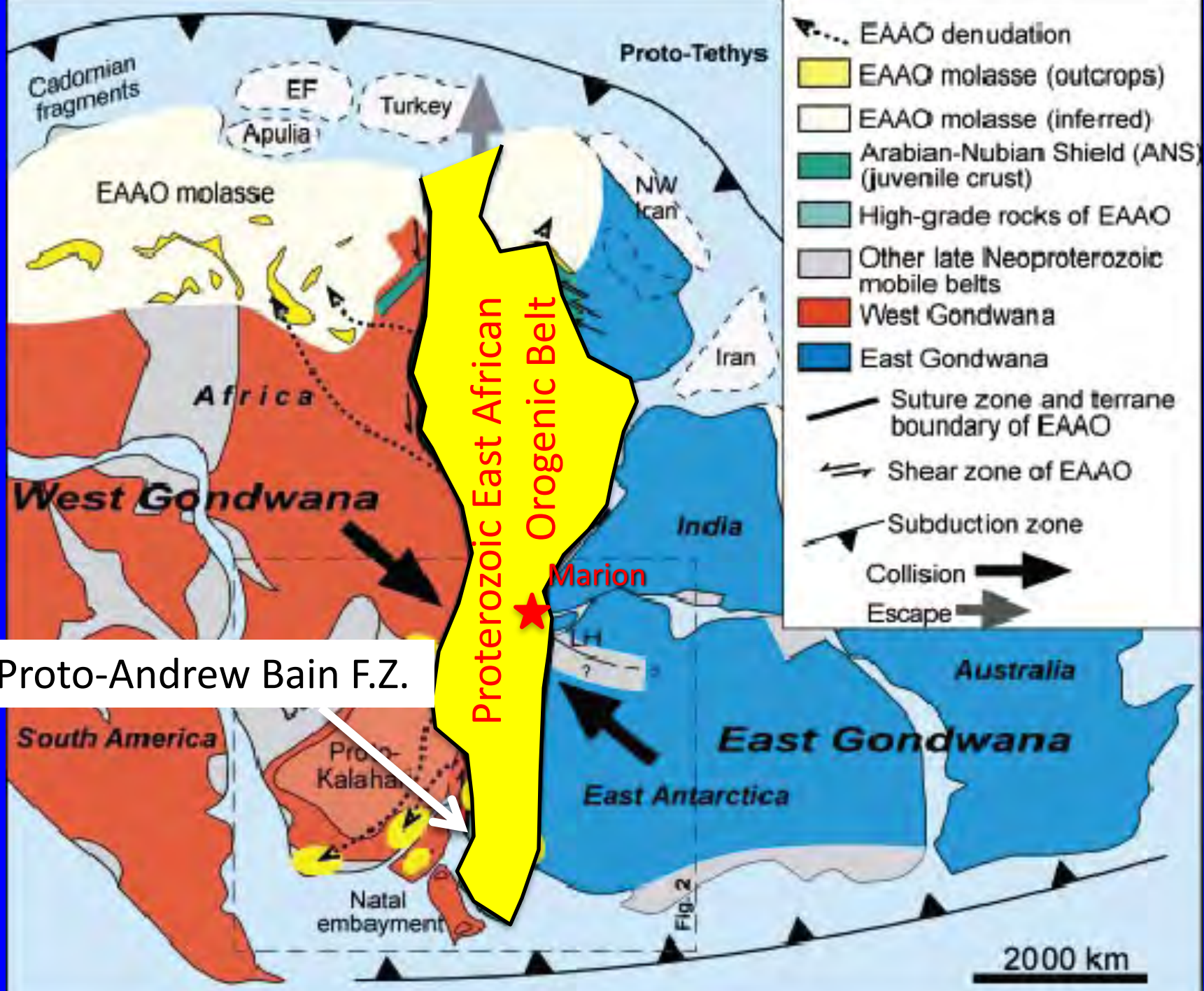
Despite being 50° C hotter, the refractory peridotite produces < 50% as much melt as the fertile peridotite due to the lower melting point of the latter.

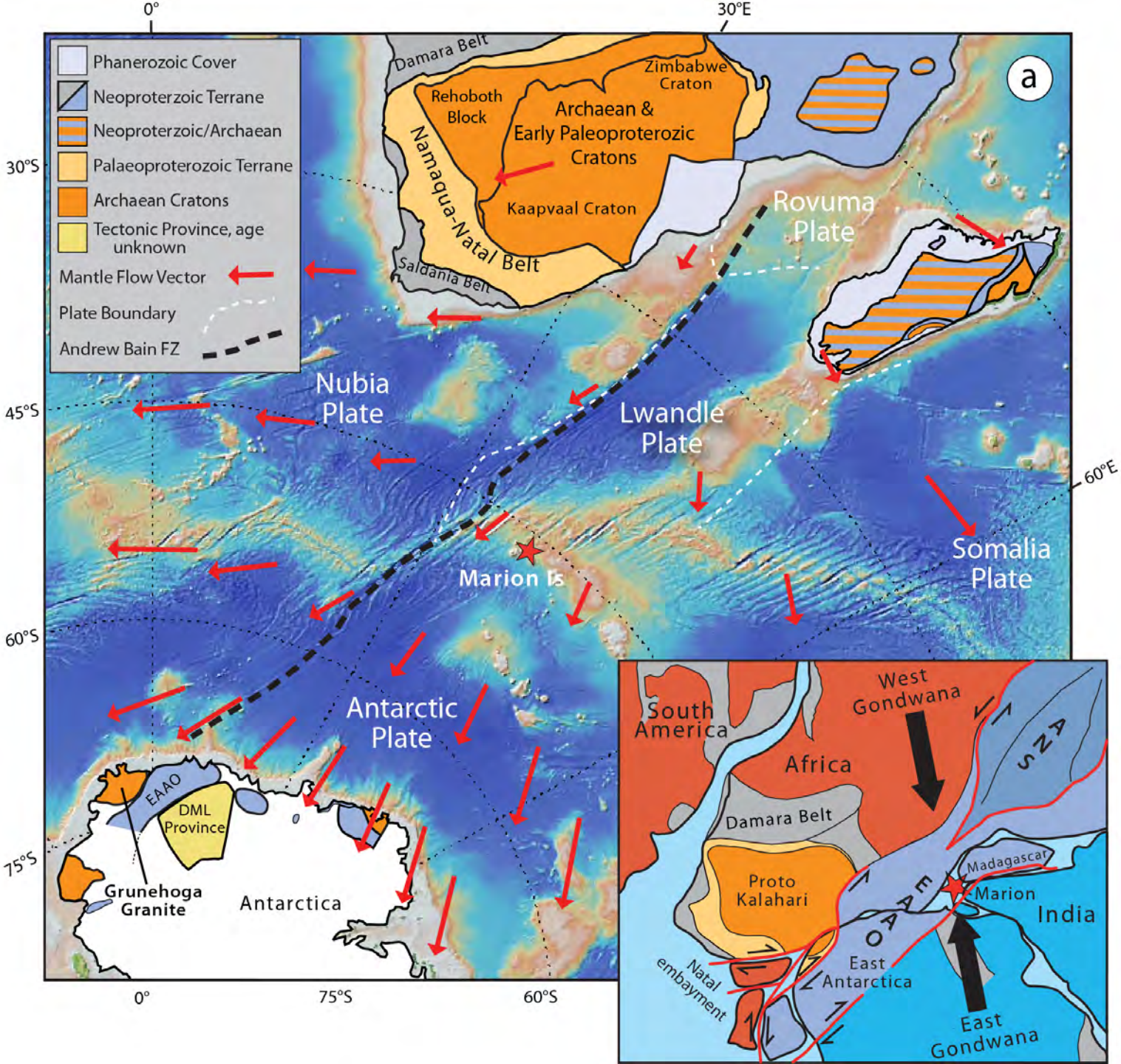
So in this case, the crust at the top of the rise would be thinner than at its deepest point.

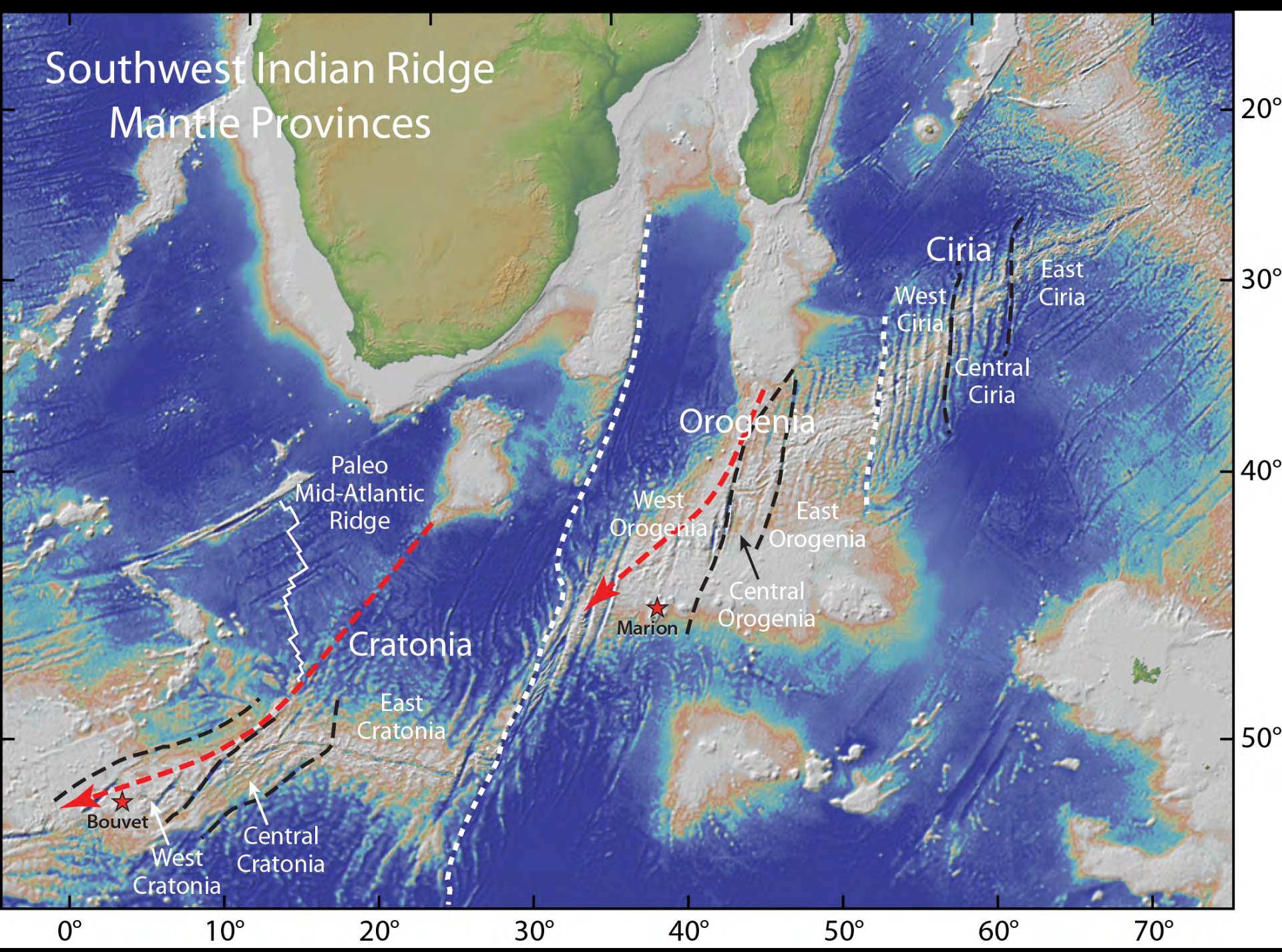
✔ The Marion Rise then must be largely supported then by buoyant depleted harzburgitic.

✔ However as the density contrast between spinel harzburgite and spinel lherzolite is small, so the buoyant layer lies below 70-km in the garnet peridotite stability field, extending down an additional ~140-200 km



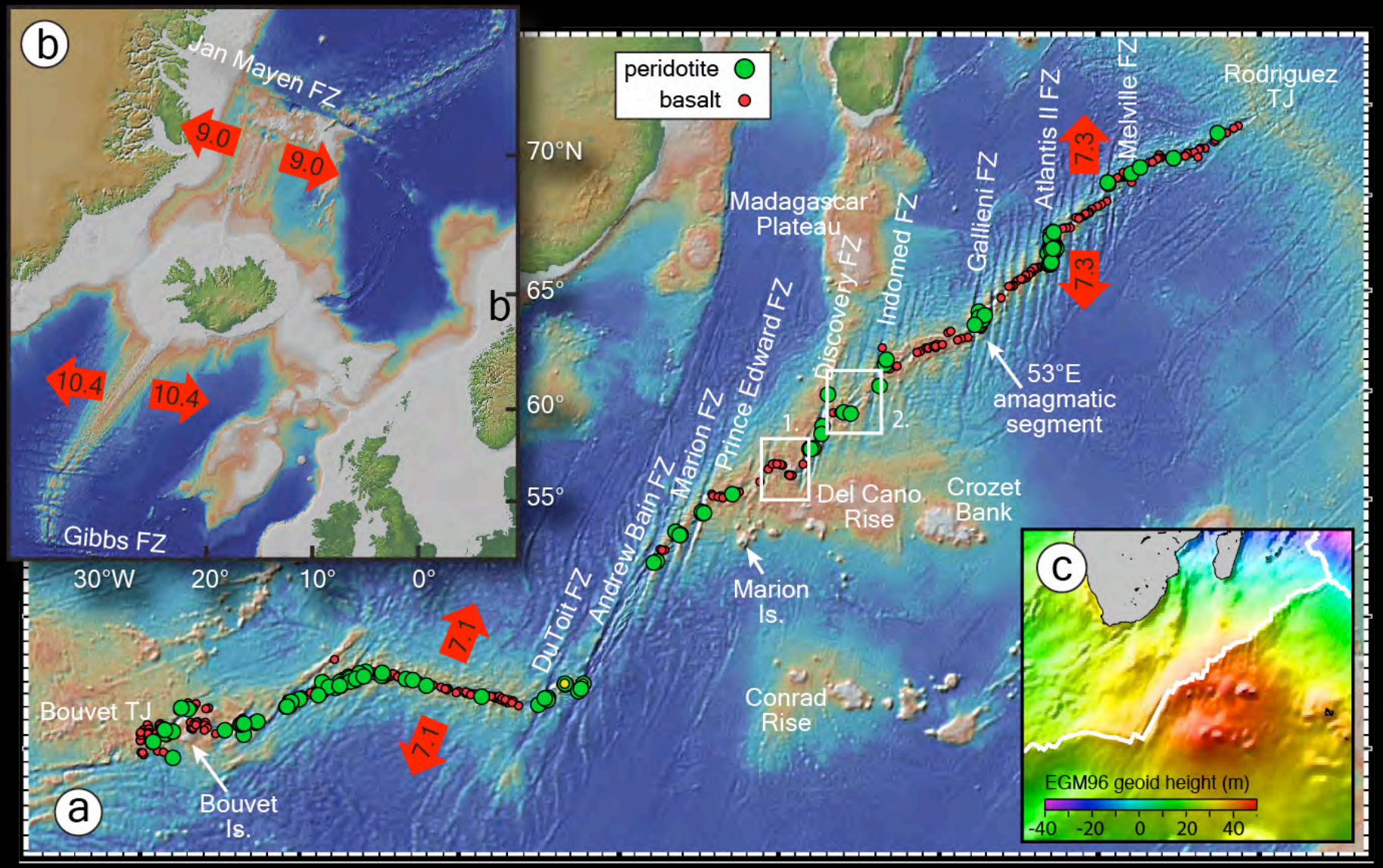

Proto-Tethys
Cadomian fragments
EF
Apulia
Turkey
EAAO molasse
NW Iran
Iran
Africa
West Gondwana
Proterozoic East African Orogenic Belt
Marion
India
LH
Australia
East Gondwana
East Antarctica
South America
Proto-Kalahari
Natal embayment
Fig. 2
2000 km
Proto-Andrew Bain F.Z.
EAAO denudation
EAAO molasse (outcrops)
EAAO molasse (inferred)
Arabian-Nubian Shield (ANS) (juvenile crust)
High-grade rocks of EAAO
Other late Neoproterozoic mobile belts
West Gondwana
East Gondwana
Suture zone and terrane boundary of EAAO
Shear zone of EAAO
Subduction zone
Collision
Escape

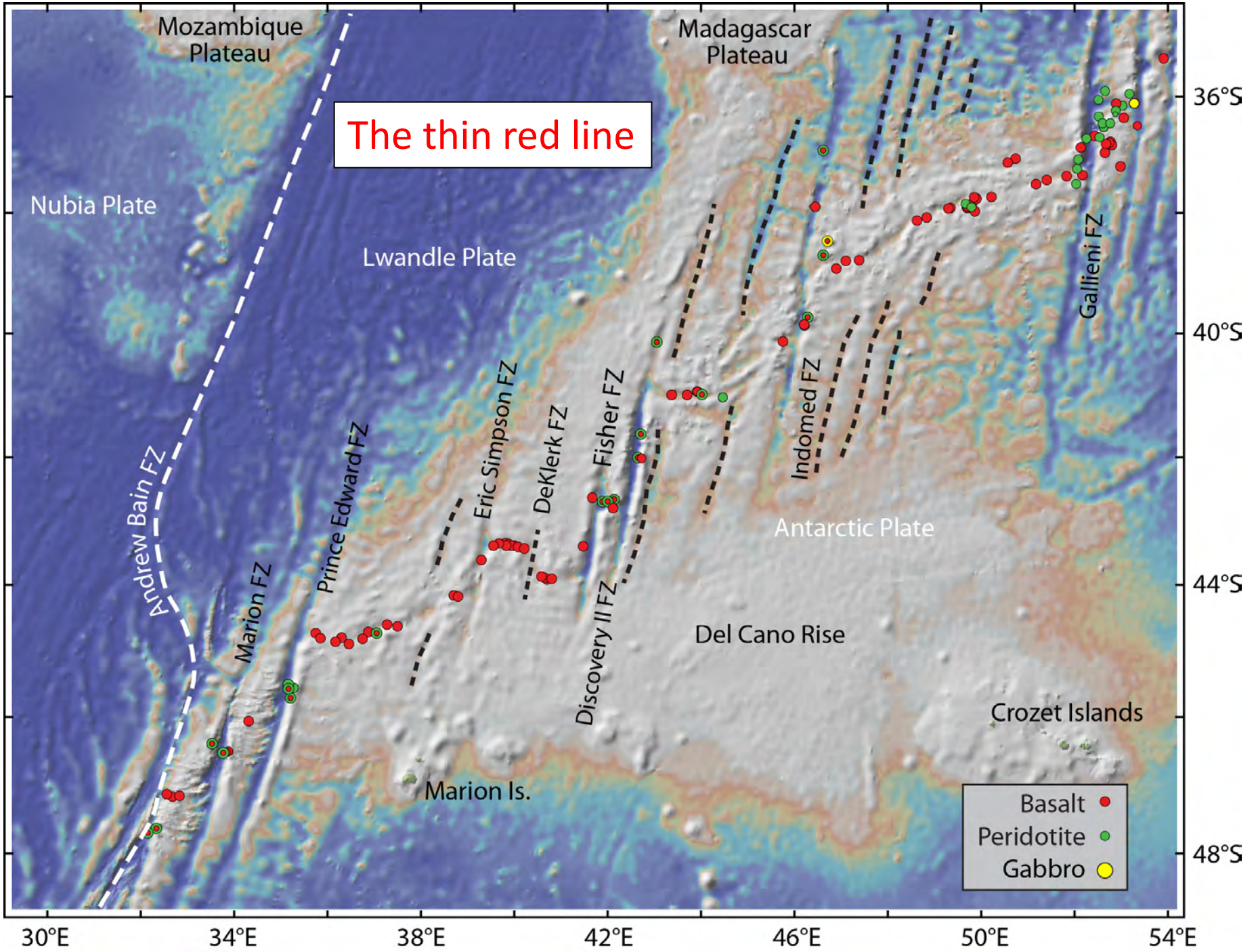

0°
30°E
30°S
45°S
60°S
75°S
60°E
a
Phanerozoic Cover
Neoproterzoic Terrane
Neoproterzoic/Archaean
Palaeoproterozoic Terrane
Archaean Cratons
Tectonic Province, age unknown
Mantle Flow Vector
Plate Boundary
Andrew Bain FZ
Damara Belt
Zimbabwe Craton
Rehoboth Block
Archaean & Early Paleoproterozic Cratons
Namaqua-Natal Belt
Kaapvaal Craton
Saldania Belt
Rovuma Plate
Nubia Plate
Lwandle Plate
Somalia Plate
Marion Is
Antarctic Plate
EAAO
DML Province
Grunehoga Granite
Antarctica
0°
75°S
60°S
South America
West Gondwana
Africa
SSZ
Damara Belt
Proto Kalahari
Madagascar
Marion
India
OAM
East Antarctica
Natal embayment
East Gondwana

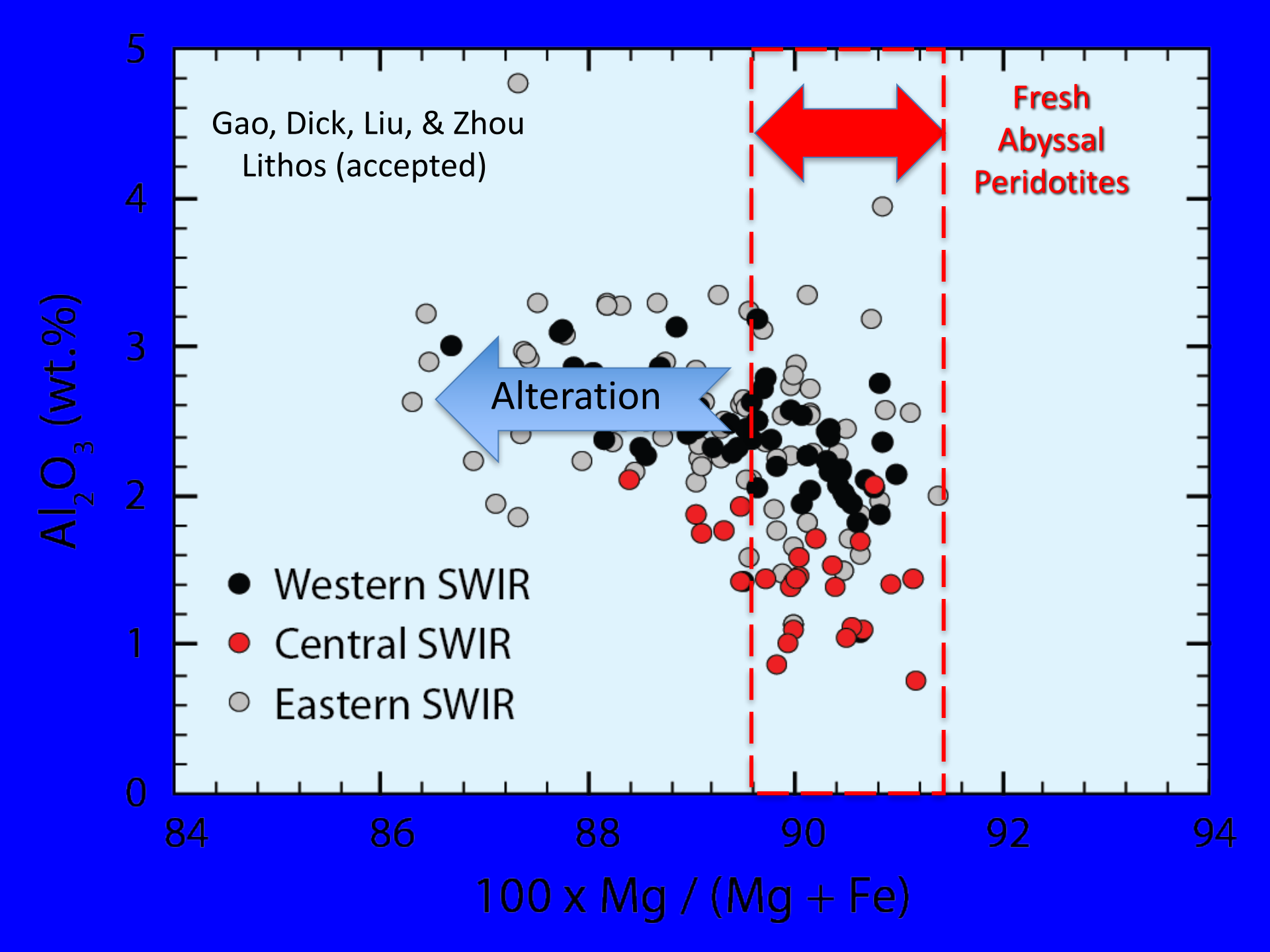

Southwest Indian Ridge
Mantle Provinces
Ciria
East Ciria
West Ciria
Central Ciria
Orogenia
West Orogenia
East Orogenia
Central Orogenia
Marion
Paleo Mid-Atlantic Ridge
Cratonia
East Cratonia
Central Cratonia
West Cratonia
Bouvet
20°
30°
40°
50°
0°
10°
20°
30°
40°
50°
60°
70°

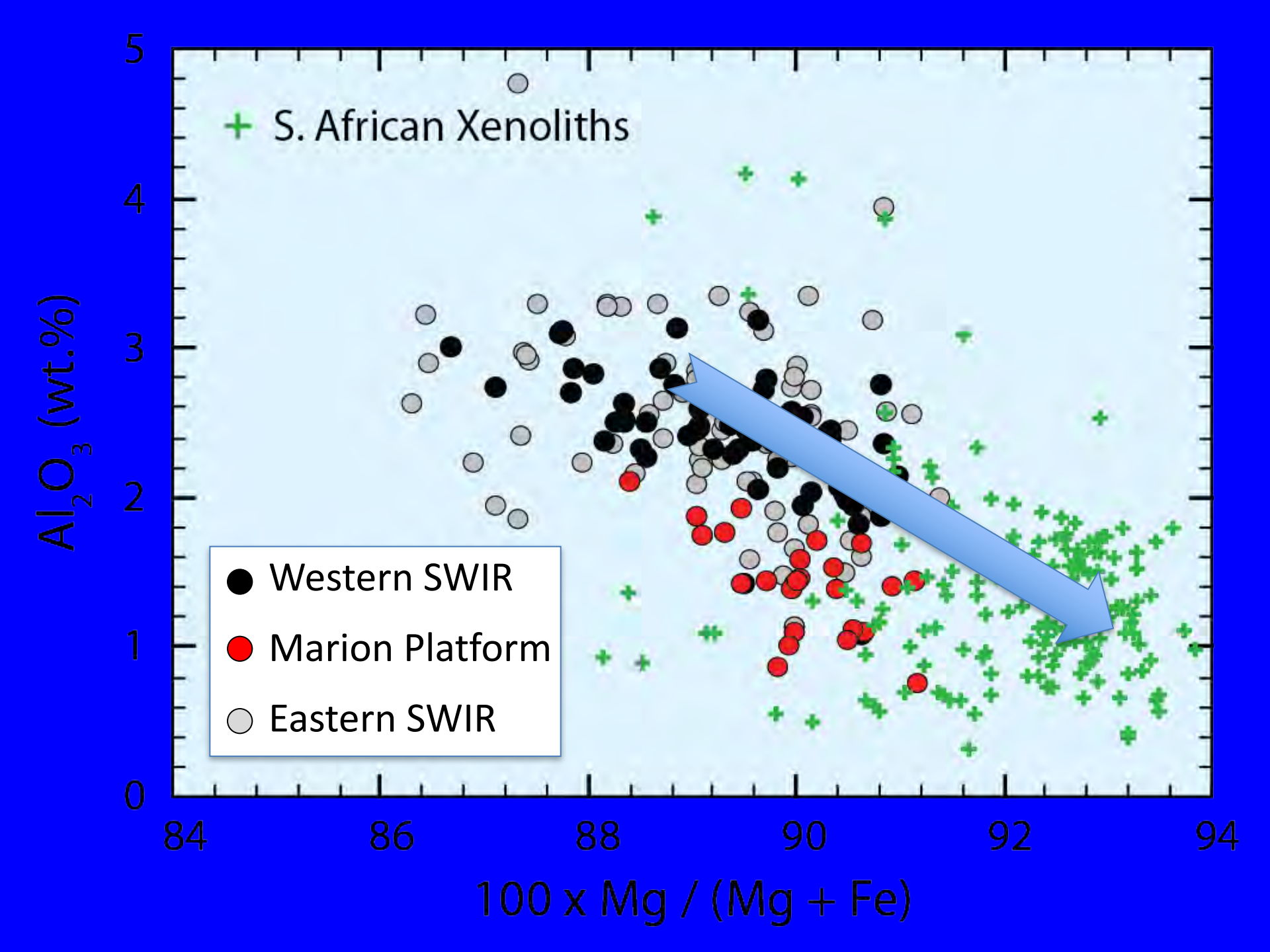
Status and plans for IODP, MG&G, research in the Indian Ocean – *Henry Dick (WHOI)*

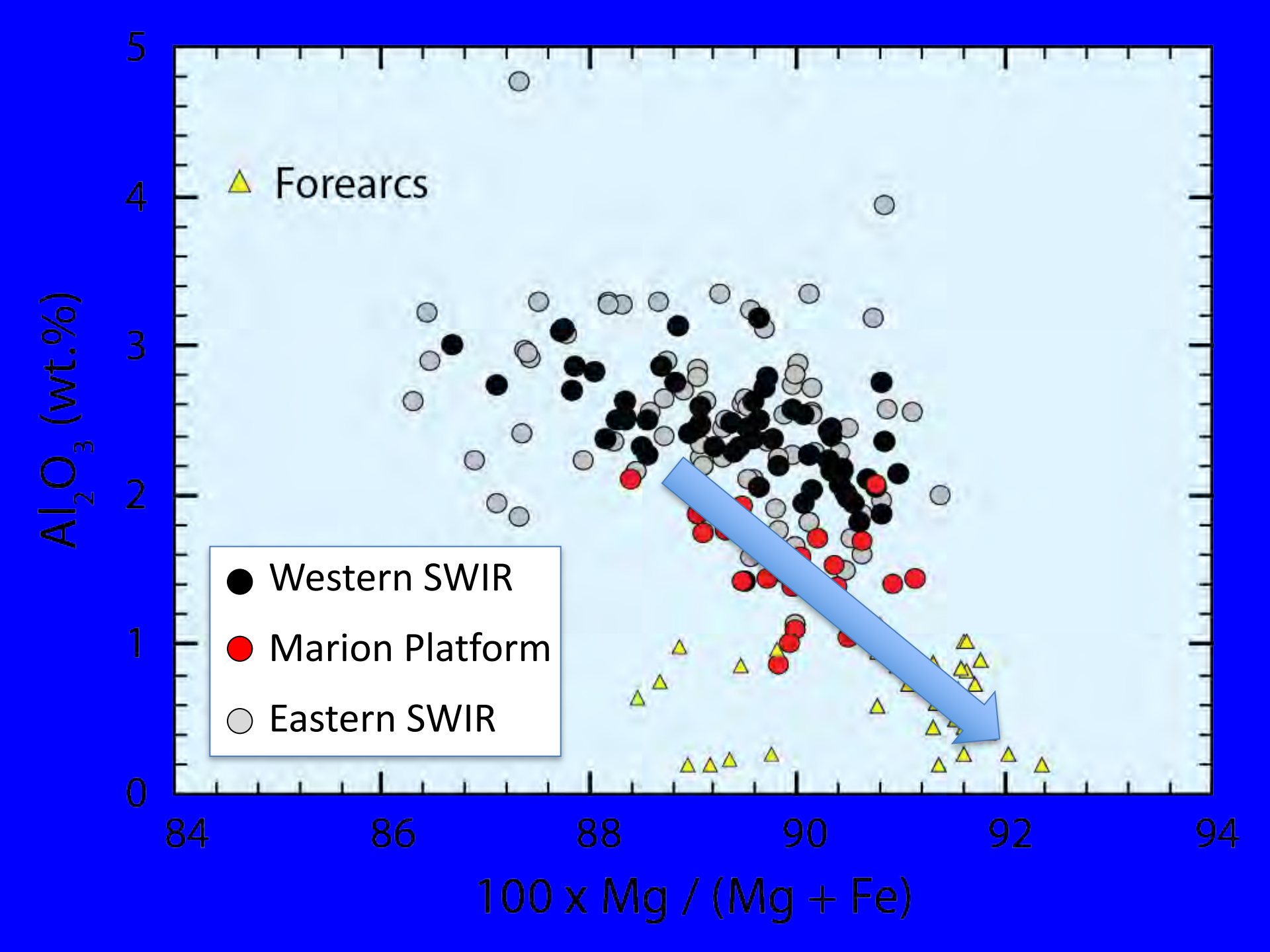
US — German — China Marion Rise Expedition

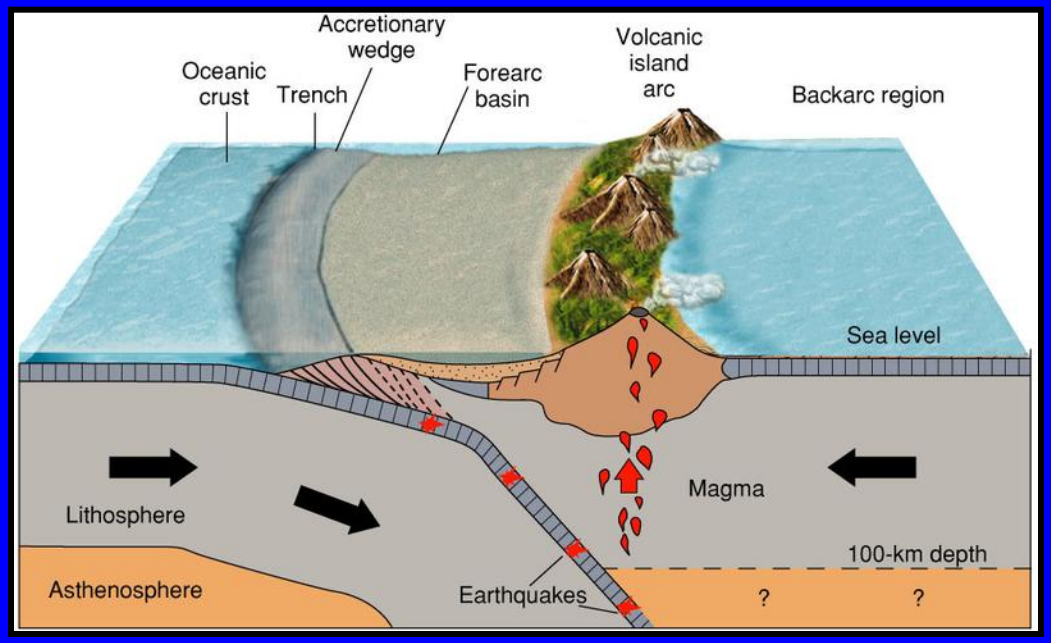


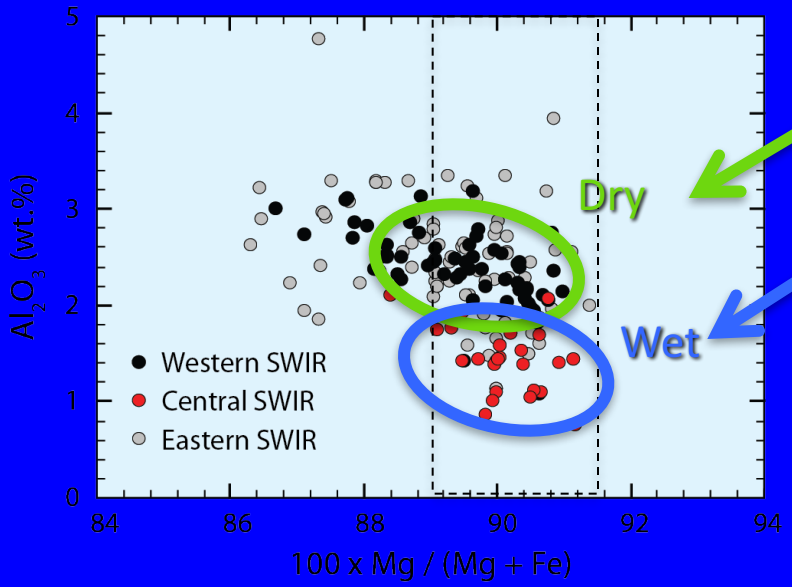

Mozambique Plateau
Madagascar Plateau
The thin red line
Nubia Plate
Lwandle Plate
Antarctic Plate
Del Cano Rise
Crozet Islands
Marion Is.
Andrew Bain FZ
Marion FZ
Prince Edward FZ
Eric Simpson FZ
DeKlerk FZ
Fisher FZ
Discovery II FZ
Indomed FZ
Gallieni FZ
Basalt
Peridotite
Gabbro
36°S
40°S
44°S
48°S
30°E
34°E
38°E
42°E
46°E
50°E
54°E

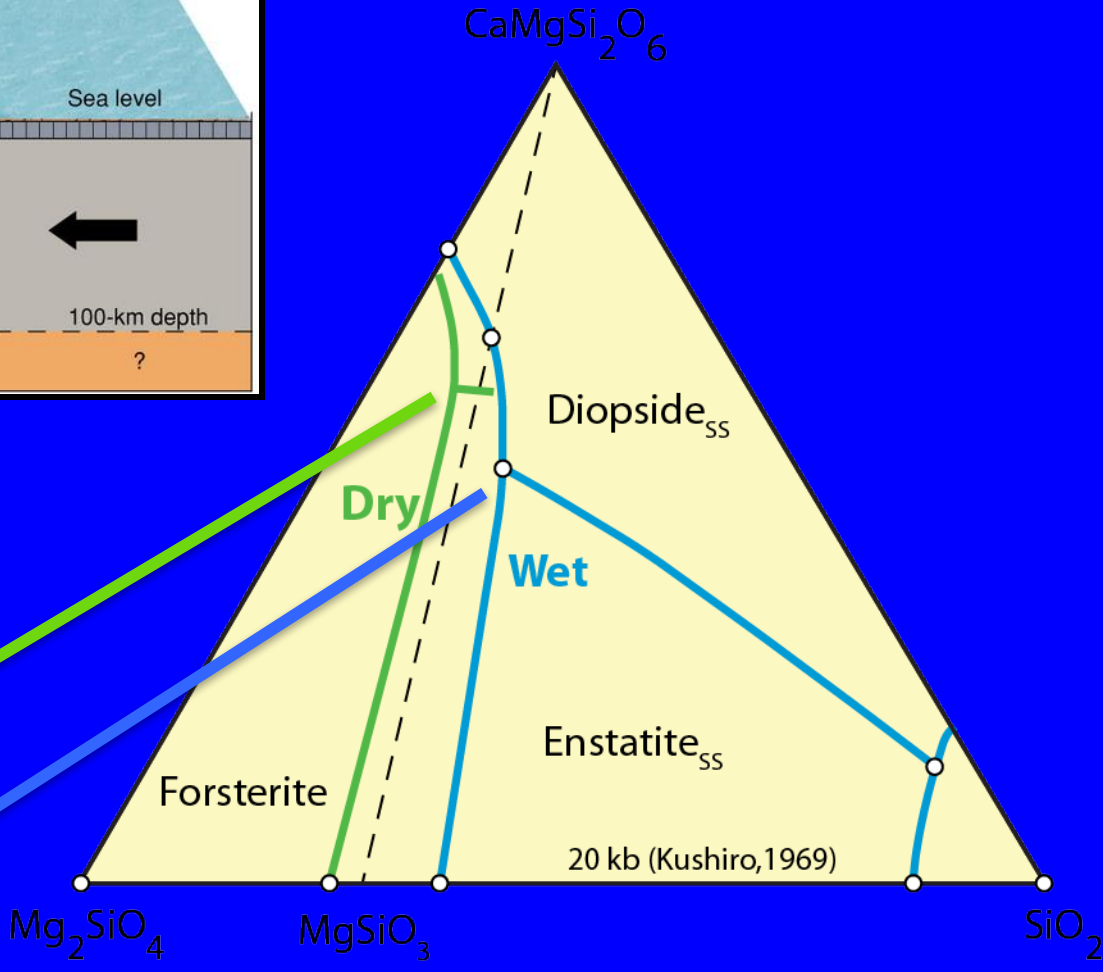

Gao, Dick, Liu, & Zhou
Lithos (accepted)
Fresh
Abyssal
Peridotites
Alteration
Western SWIR
Central SWIR
Eastern SWIR
Al_2O_3 (wt.%)
100 x Mg / (Mg + Fe)
0
1
2
3
4
5
84
86
88
90
92
94


S. African Xenoliths
Western SWIR
Marion Platform
Eastern SWIR
Al_2O_3 (wt.%)
100 x Mg / (Mg + Fe)
0
1
2
3
4
5
84
86
88
90
92
94


Forearcs
Western SWIR
Marion Platform
Eastern SWIR
Al_2O_3 (wt.%)
100 x Mg / (Mg + Fe)
0
1
2
3
4
5
84
86
88
90
92
94

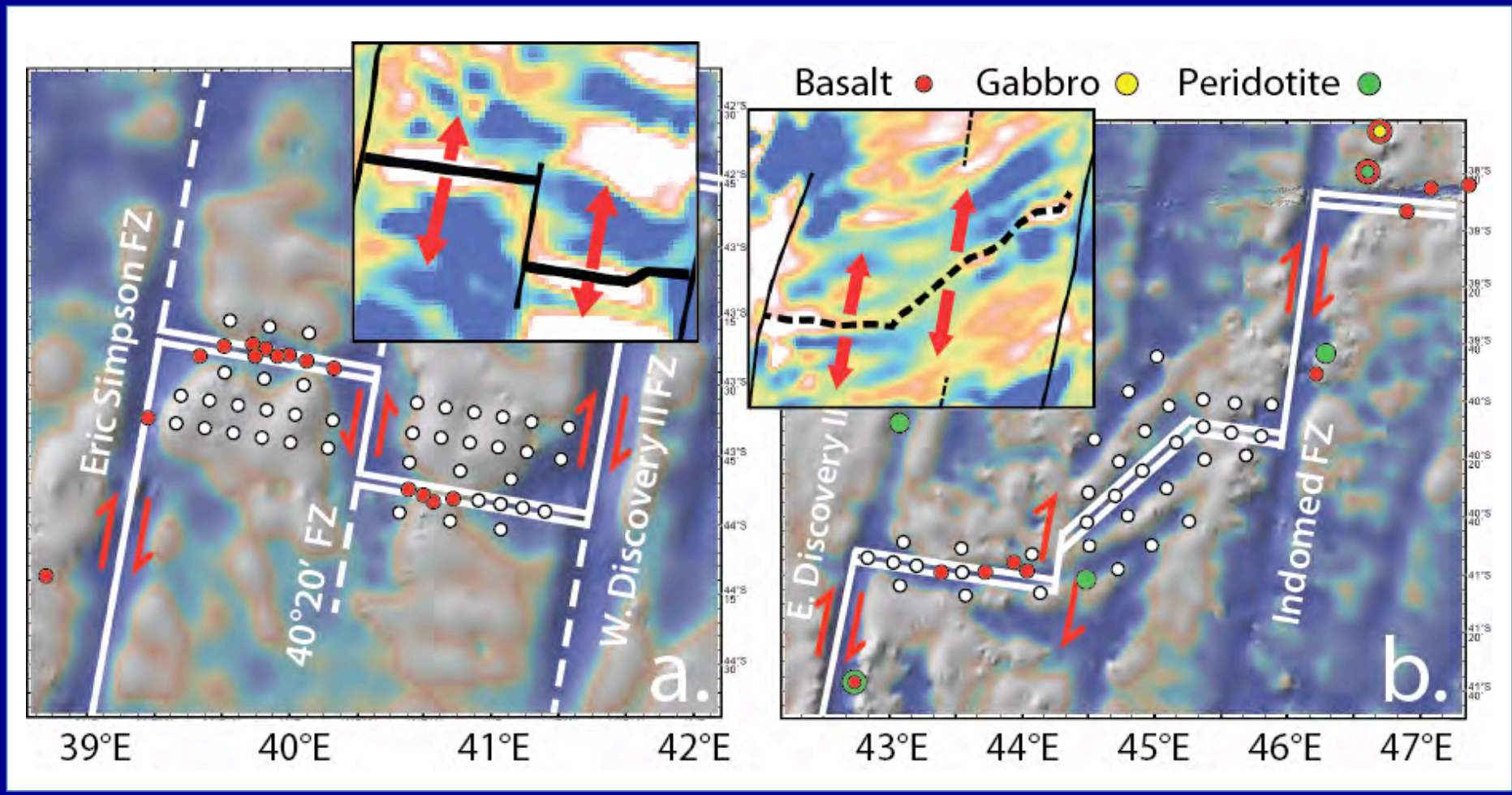

Accretionary wedge
Oceanic crust
Trench
Forearc basin
Volcanic island arc
Backarc region
Sea level
Lithosphere
Magma
100-km depth
Asthenosphere
Earthquakes
?
?


Dry
Wet
Western SWIR
Central SWIR
Eastern SWIR
Al_2O_3 (wt.%)
100 x Mg / (Mg + Fe)
0
1
2
3
4
5
84
86
88
90
92
94


$CaMgSi_2O_6$
$Diopside_{ss}$
Dry
Wet
$Enstatite_{ss}$
Forsterite
20 kb (Kushiro,1969)
Mg_2SiO_4
$MgSiO_3$
SiO_2

US — China Focus Sites

Multibeam, gravity, and Magnetics Survey with Dredging and Near Bottom Mapping with Sentry



Scheduled for 36 days port to port on Thomas G. Thompson
February – March 2019

Follow on Sonne Program

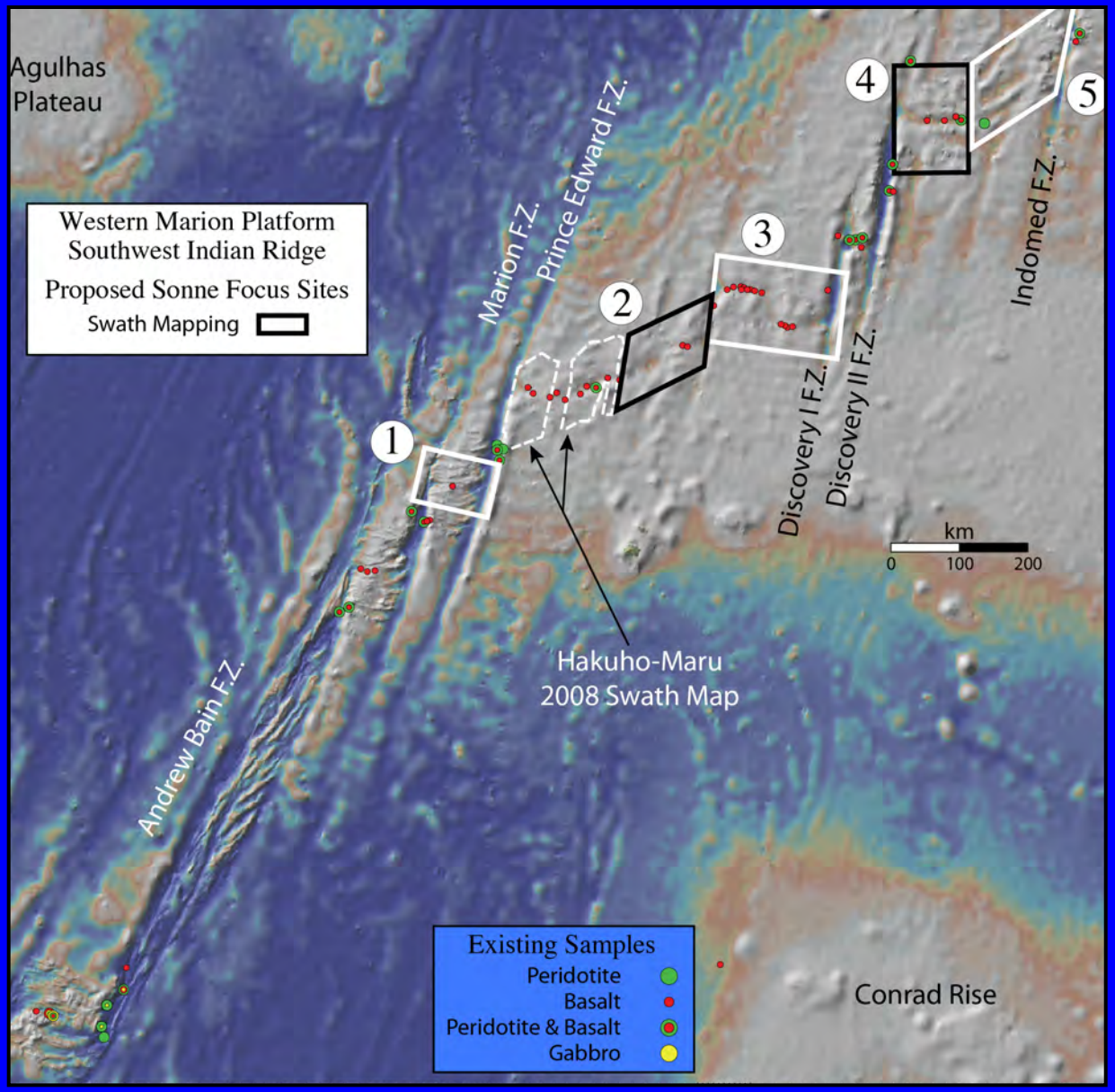
Juergen Koepke, Leibniz University Hanover, Chief Scientist

Approved for Scheduling, likely late 2019 or 2020

Multibeam, and surfaced towed magnetics and gravity
Dredging
ROV Dives

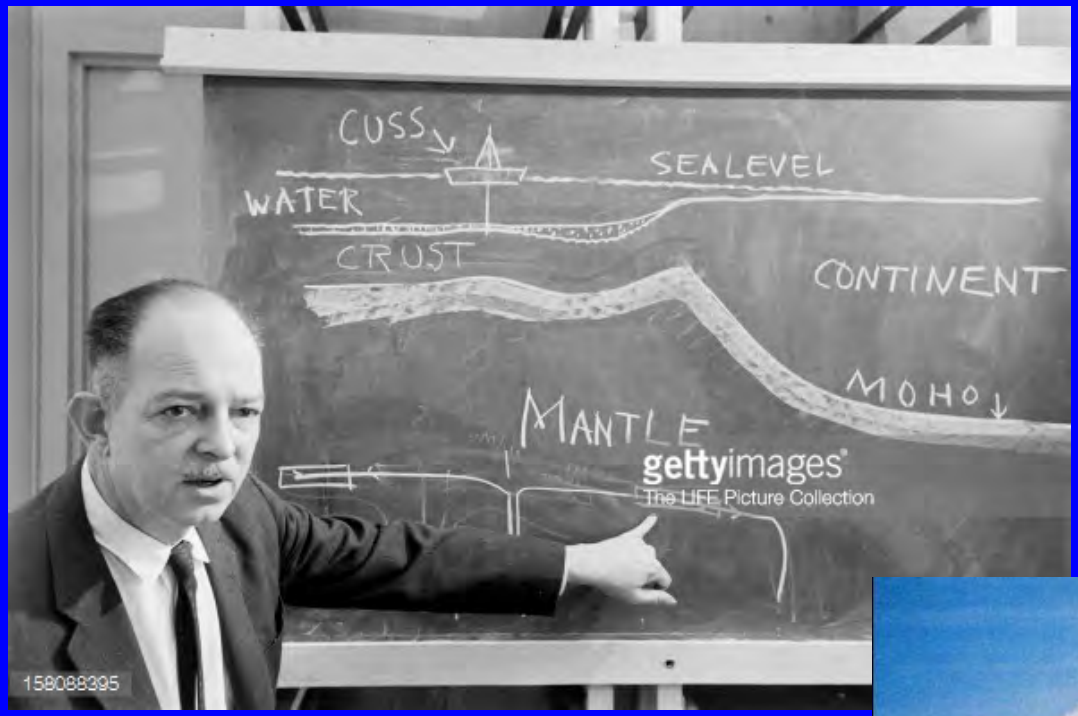
Map and sample areas 2 & 4

Follow on Diving in US-China Focus Sites



Atlantis Bank Indian Ocean & The Journey to Moho

Project Mohole



Walter Munk, Harry Hess
&
The American Miscellaneous Society

1961
CUSS 1 Drilled 601 m into seismic layer 2, 40 miles from Guadalupe, Mexico

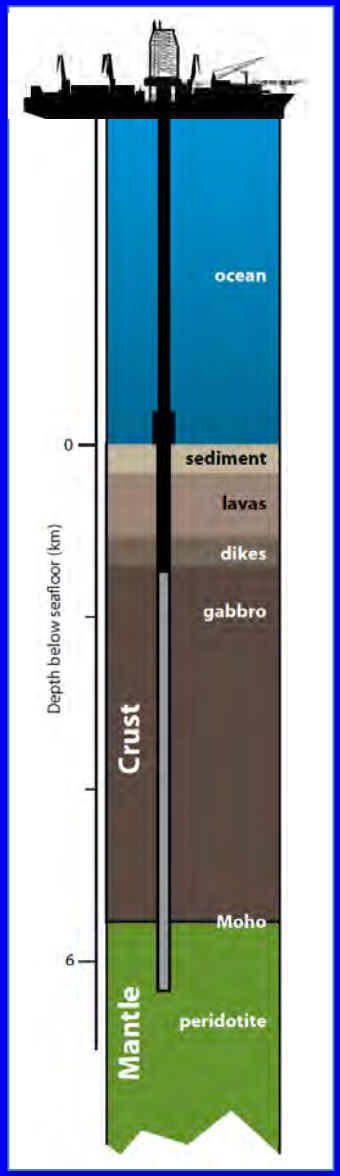
MoHole in the 21st Century

SloMo (Moho at a Slow Spreading Ridge) - The Atlantis Bank gabbro massif on the SW Indian Ridge – Expedition 360, 789-m hole, leg 2 approved.

Phase 1: JOIDES Resolution to drill 3 km to determine if the crust-mantle boundary lies above Moho the crust-mantle boundary.

Phase 2: Chikyu to drill 6 km through Moho ~5.5 km.

M2M (MoHole To the Mantle) – intact East Pacific Rise Crust in the Pacific – 2023?



SloMo Objectives:

1) Test the hypothesis that the Moho may not be the Crust-Mantle boundary

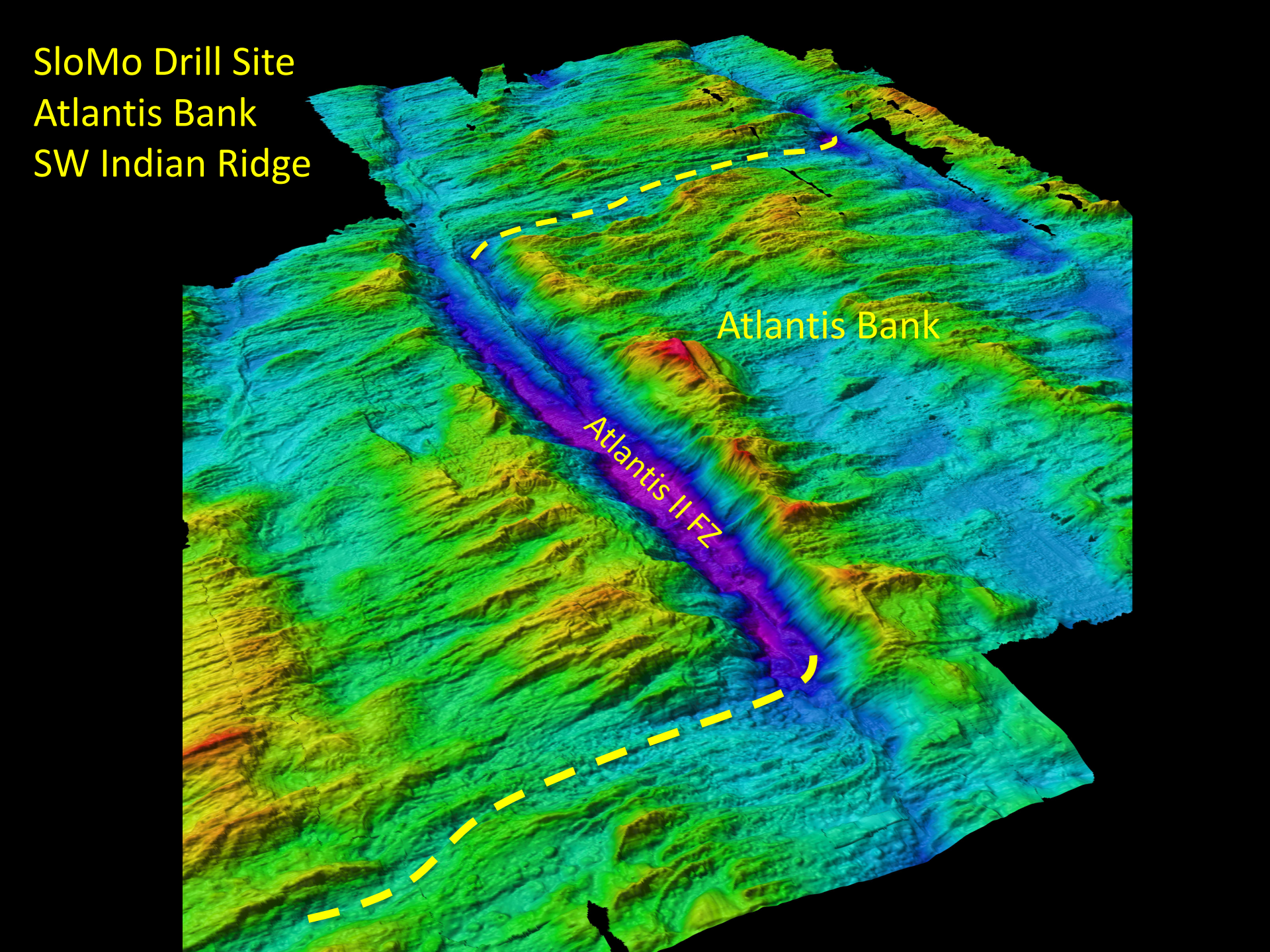
Is Moho a serpentinization front at slower spreading ridges?

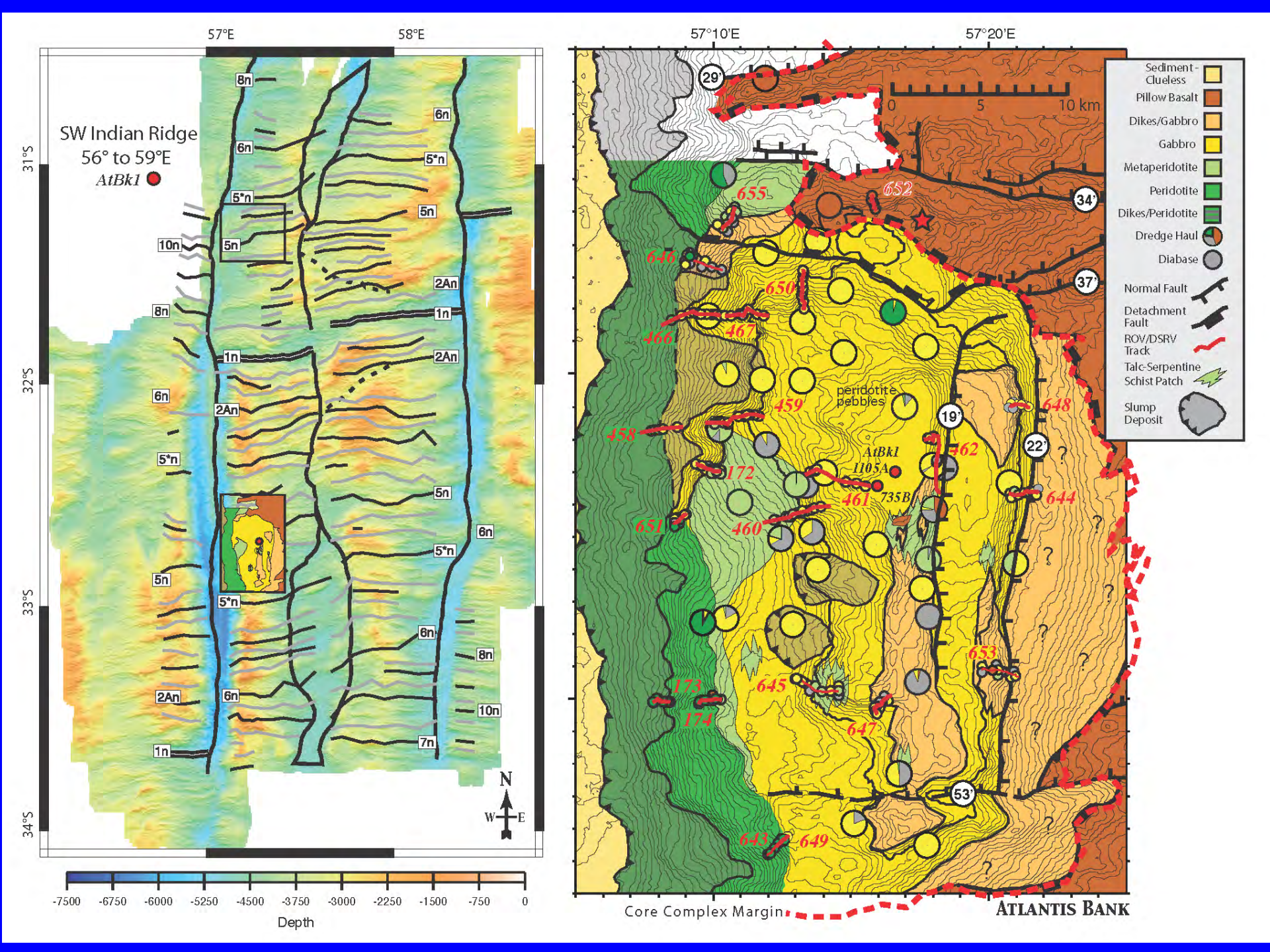
2) Recover a full section of the oceanic lower crust

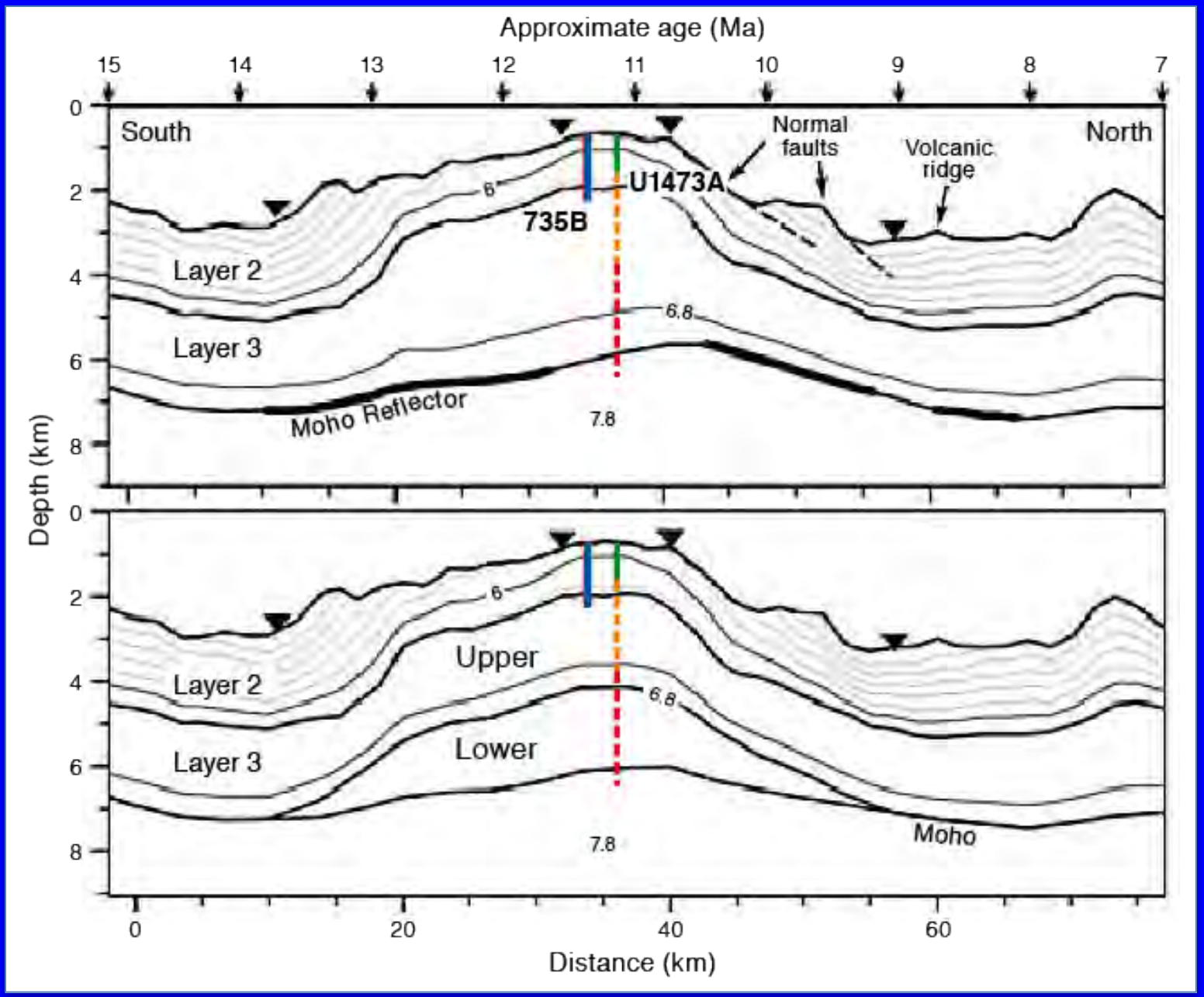
3) What is the carbon budget in the lower crust & shallow mantle

4) What is the microbiological inventory of the crust and shallow mantle

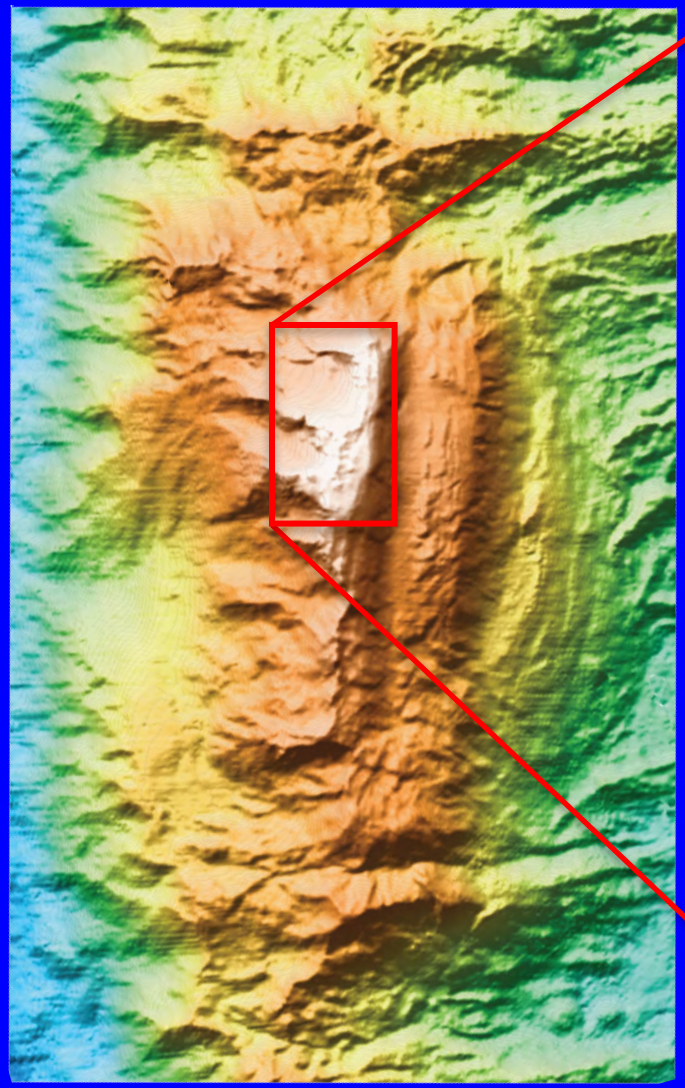
Is there a new planetary biosphere between the crust-mantle boundary and the Moho?

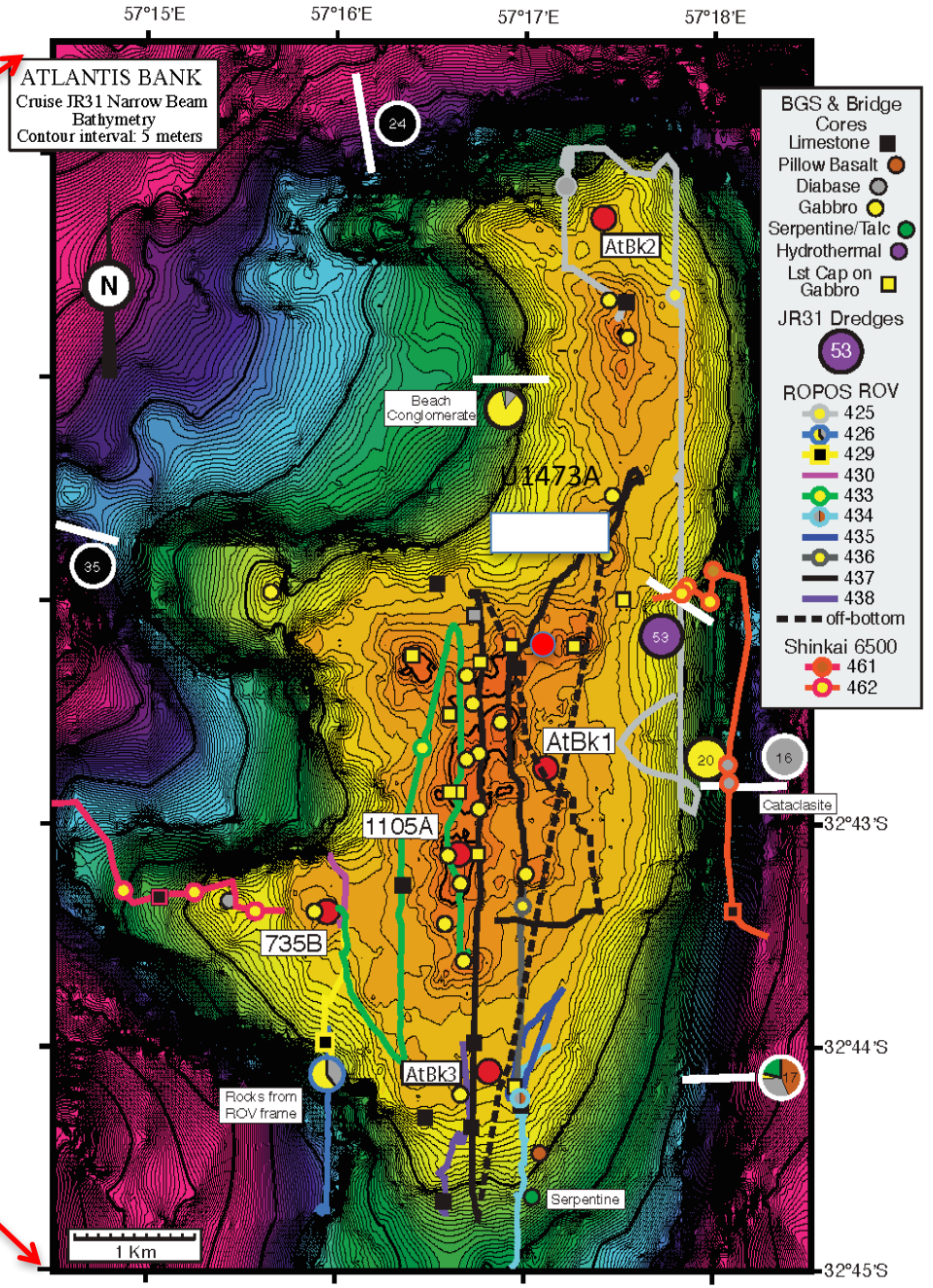

SloMo Drill Site
Atlantis Bank
SW Indian Ridge
Atlantis Bank
Atlantis II FZ


57°E
58°E
31°S
32°S
33°S
34°S
SW Indian Ridge
56° to 59°E
AtBk1
8n
6n
5*n
5n
10n
2An
1n
7n
N
W
E
-7500
-6750
-6000
-5250
-4500
-3750
-3000
-2250
-1500
-750
0
Depth
57°10'E
57°20'E
29'
34'
37'
19'
22'
53'
0
5
10 km
655
652
646
650
466
467
459
458
172
461
460
651
462
644
648
653
645
173
174
647
643
649
peridotite pebbles
AtBk1 1105A
735B
Sediment - Clueless
Pillow Basalt
Dikes/Gabbro
Gabbro
Metaperidotite
Peridotite
Dikes/Peridotite
Dredge Haul
Diabase
Normal Fault
Detachment Fault
ROV/DSRV Track
Talc-Serpentine Schist Patch
Slump Deposit
Core Complex Margin
ATLANTIS BANK


Approximate age (Ma)
15
14
13
12
11
10
9
8
7
South
North
Normal faults
Volcanic ridge
U1473A
735B
6
6.8
7.8
Layer 2
Layer 3
Moho Reflector
Upper
Lower
Moho
Depth (km)
0
2
4
6
8
0
20
40
60
Distance (km)

High-resolution 2-m contour map of the Atlantis Bank Platform





SloMo — Current Status

Leg 1 of Phase 1 is complete – Hole U1473A is open and can be reoccupied and deepened.

However, the hole is compromised by an unstable fault zone in the upper 500-m
an attempt on Expedition 362T failed to cement the fault zone, and it remains unstable.

Option 1: Return to Hole U1473A, finish cementing if possible, and then attempt to drill to 3-km to meet the Phase 1 objective of reaching the crust-mantle boundary.

Option 2: Return to Site 735 where Hole 735B was drilled to 1508 m with no significant problems or obstacles.
Leg 1: Drill to 1500-m with new hard rock drill bits provided by industry
Leg 2: Core ahead to 3,000 m

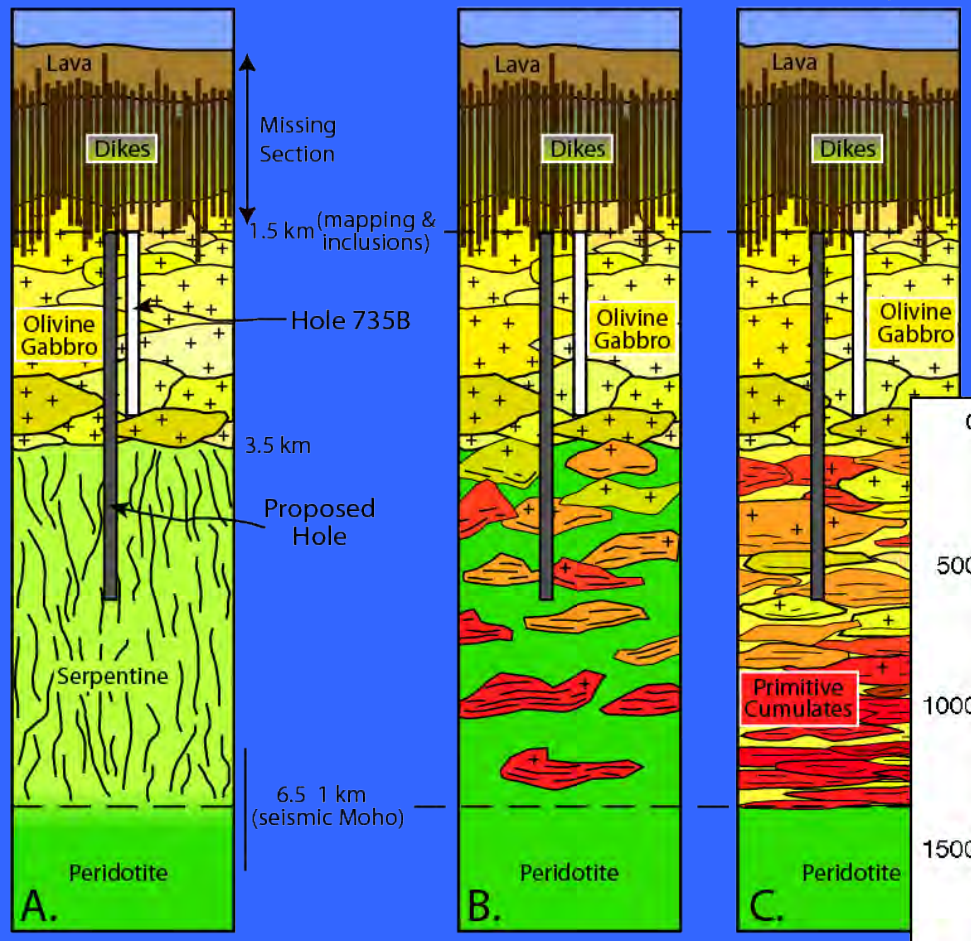
A decision on which approach will be made at the Deep Hard Rock Drilling Working Group meeting at TAMU this fall in October

Likely date for return is 2020.

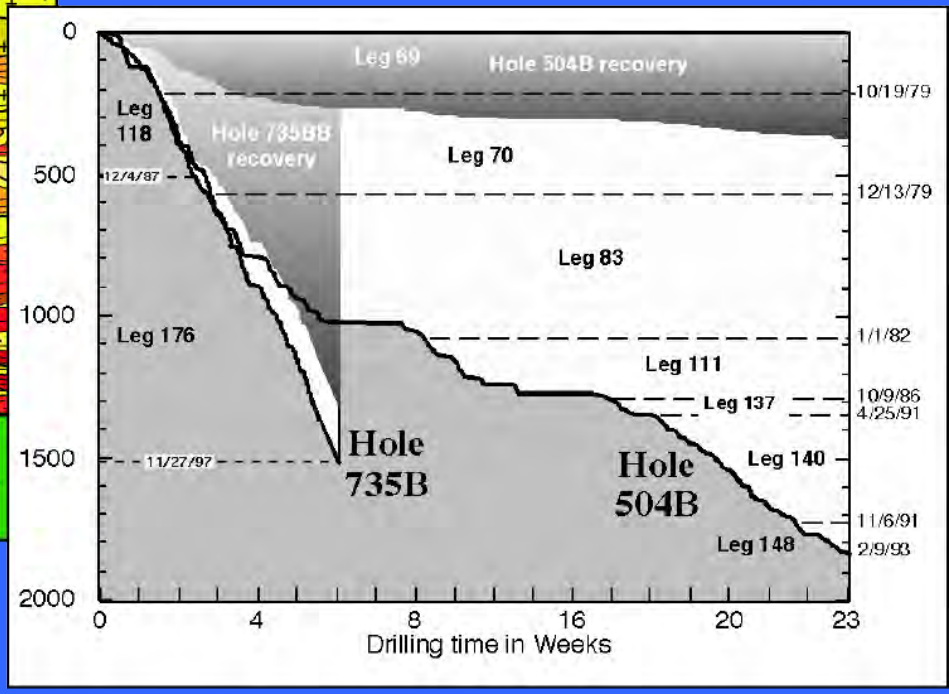
SloMo – Possible Outcomes:

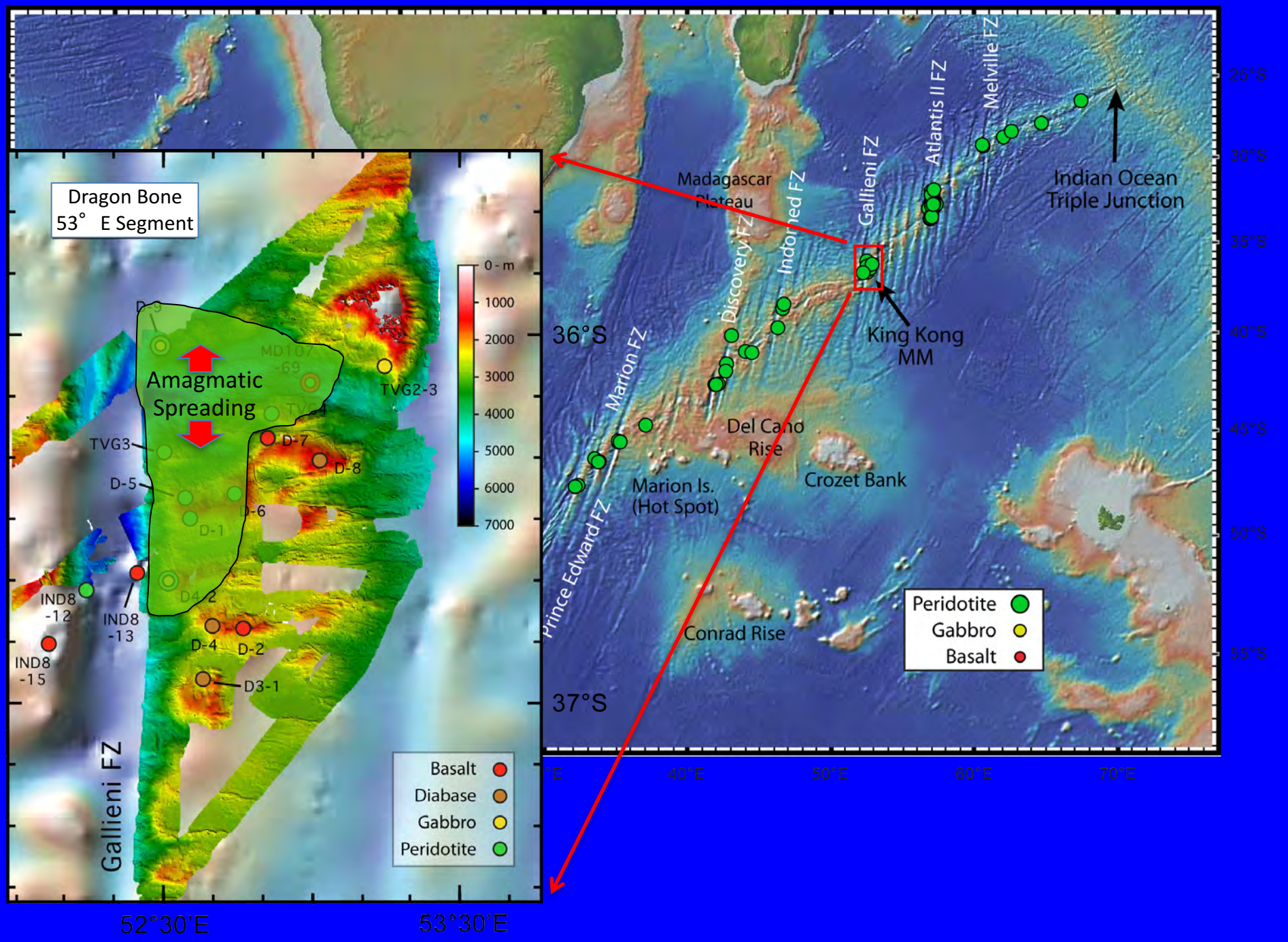
+ the one we haven't thought of.

A.

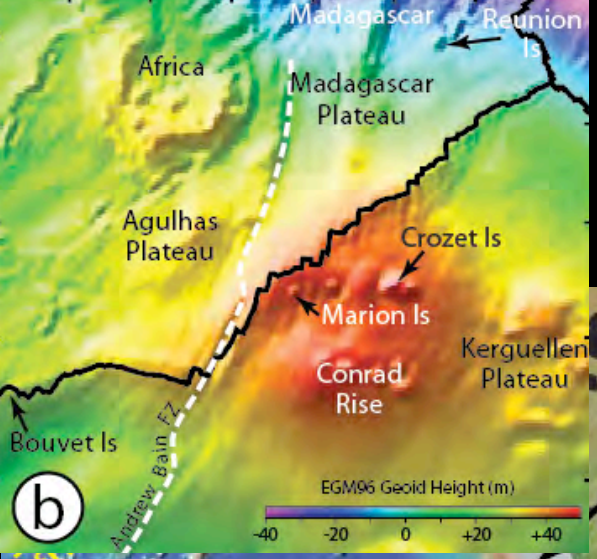


B.

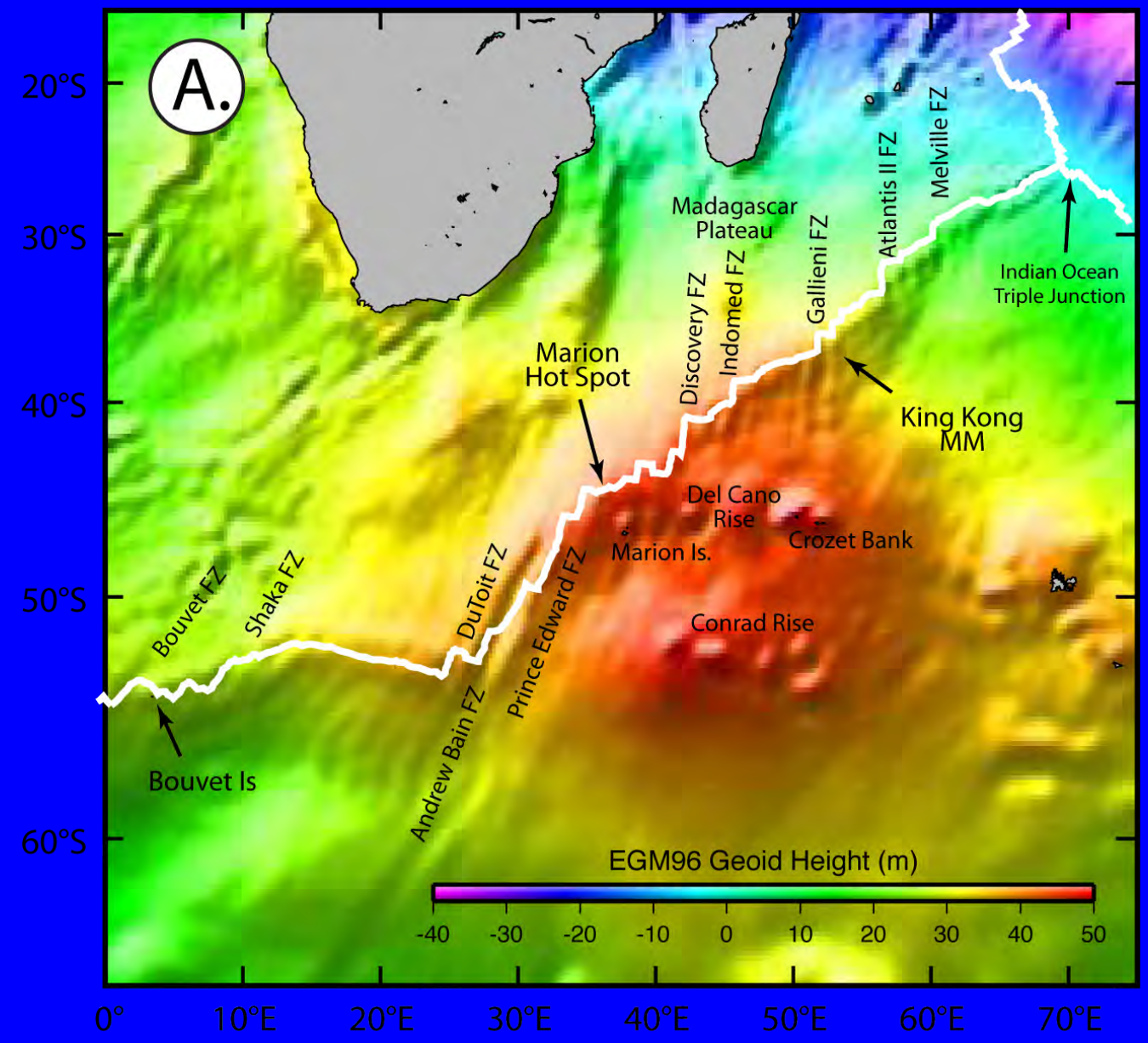



Dragon Bone
53° E Segment
Amagmatic
Spreading
0 - m
1000
2000
3000
4000
5000
6000
7000
TVG2-3
TVG3
D-7
D-8
D-5
D-6
D-1
D-4
D-2
D3-1
IND8
-12
IND8
-13
IND8
-15
Basalt
Diabase
Gabbro
Peridotite
Gallieni FZ
52°30'E
53°30'E
Madagascar
Plateau
Discovery FZ
Indomed FZ
Gallieni FZ
Atlantis II FZ
Melville FZ
Indian Ocean
Triple Junction
36°S
37°S
Marion FZ
King Kong
MM
Del Cano
Rise
Crozet Bank
Marion Is.
(Hot Spot)
Prince Edward FZ
Conrad Rise
Peridotite
Gabbro
Basalt
25°S
30°S
35°S
40°S
45°S
50°S
55°S
40°E
50°E
60°E
70°E

The Southwest Indian Ridge
Ultraslow Spreading ~14mm/yr



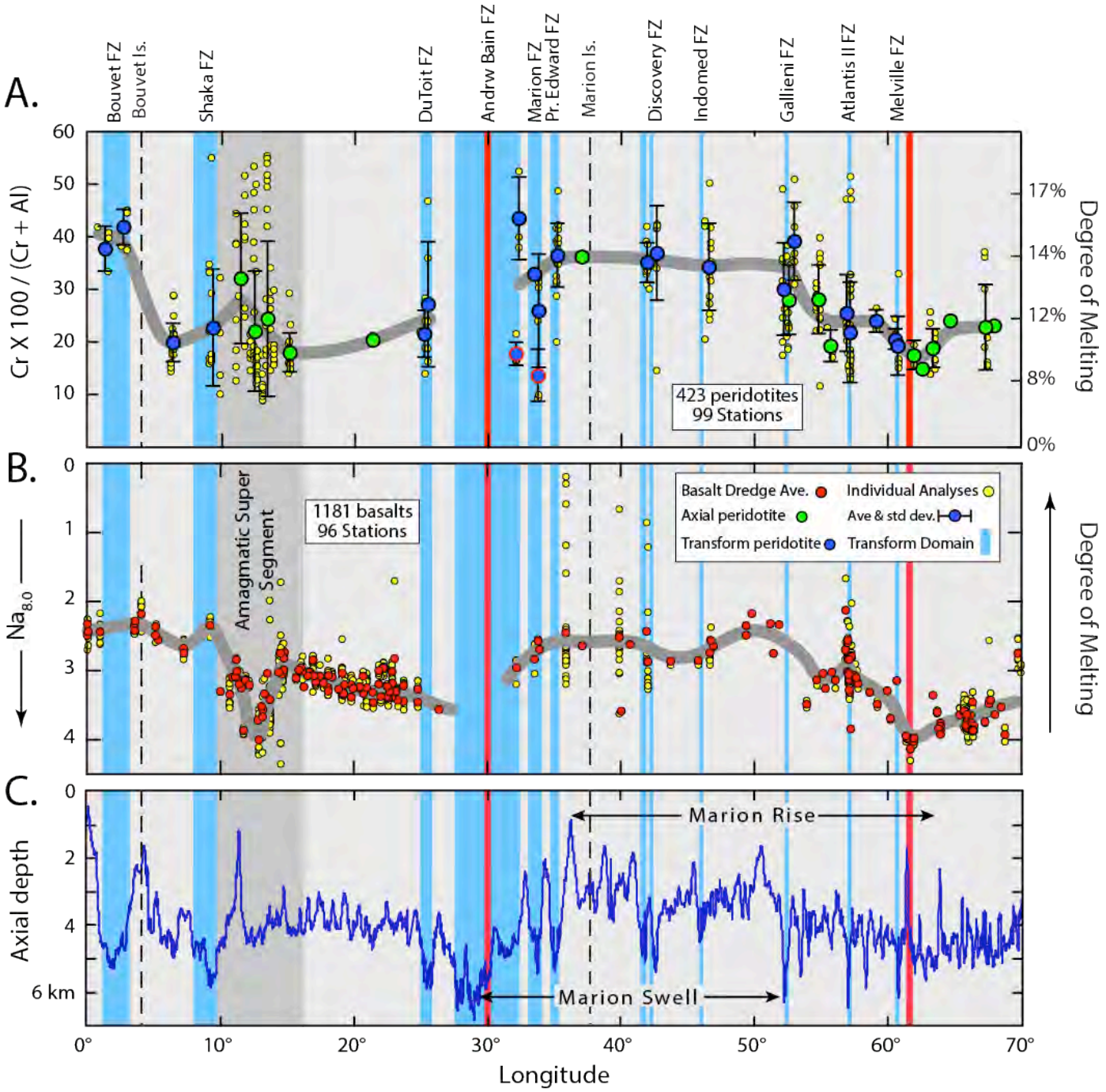
Karoo Flood Basalts
CapeTown
Madagascar Plateau
Gallieni FZ
Melville FZ
Rodriguez TJ
Agulhas Plateau
Pr. Edward FZ
Indomed FZ
Del Cano Rise
Crozet Islands
Marion Is.
Andrew Bain FZ
Kerguelen
Shaka FZ
Bouvet TJ
Conrad Rise
Bouvet Is



The SW Indian Ridge provides a direct window into the top of the Southern Oceans Geoid Anomaly.

This reveals that the source of the Marion Rise basalts is a region of anomalously depleted upper mantle.

What is the source of this previously depleted mantle ?


A.
Bouvet FZ
Bouvet Is.
Shaka FZ
DuToit FZ
Andrw Bain FZ
Marion FZ
Pr.Edward FZ
Marion Is.
Discovery FZ
Indomed FZ
Gallieni FZ
Atlantis II FZ
Melville FZ
Cr X 100 / (Cr + Al)
60
50
40
30
20
10
17%
14%
12%
8%
0%
Degree of Melting
423 peridotites
99 Stations
B.
$Na_{8.0}$
0
1
2
3
4
Amagmatic Super Segment
1181 basalts
96 Stations
Basalt Dredge Ave.
Individual Analyses
Axial peridotite
Ave & std dev.
Transform peridotite
Transform Domain
Degree of Melting
C.
Axial depth
0
2
4
6 km
Marion Rise
Marion Swell
0°
10°
20°
30°
40°
50°
60°
70°
Longitude

The SW Indian Ridge – 7,700 km long, ultraslow spreading @ 14 mm/yr full rate