NARG

Delft 2017

# Quantifying Phanerozoic km-scale vertical movements in Morocco

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ISES
Searching deeper

North Africa Research Group
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## Why focusing on vertical movements?

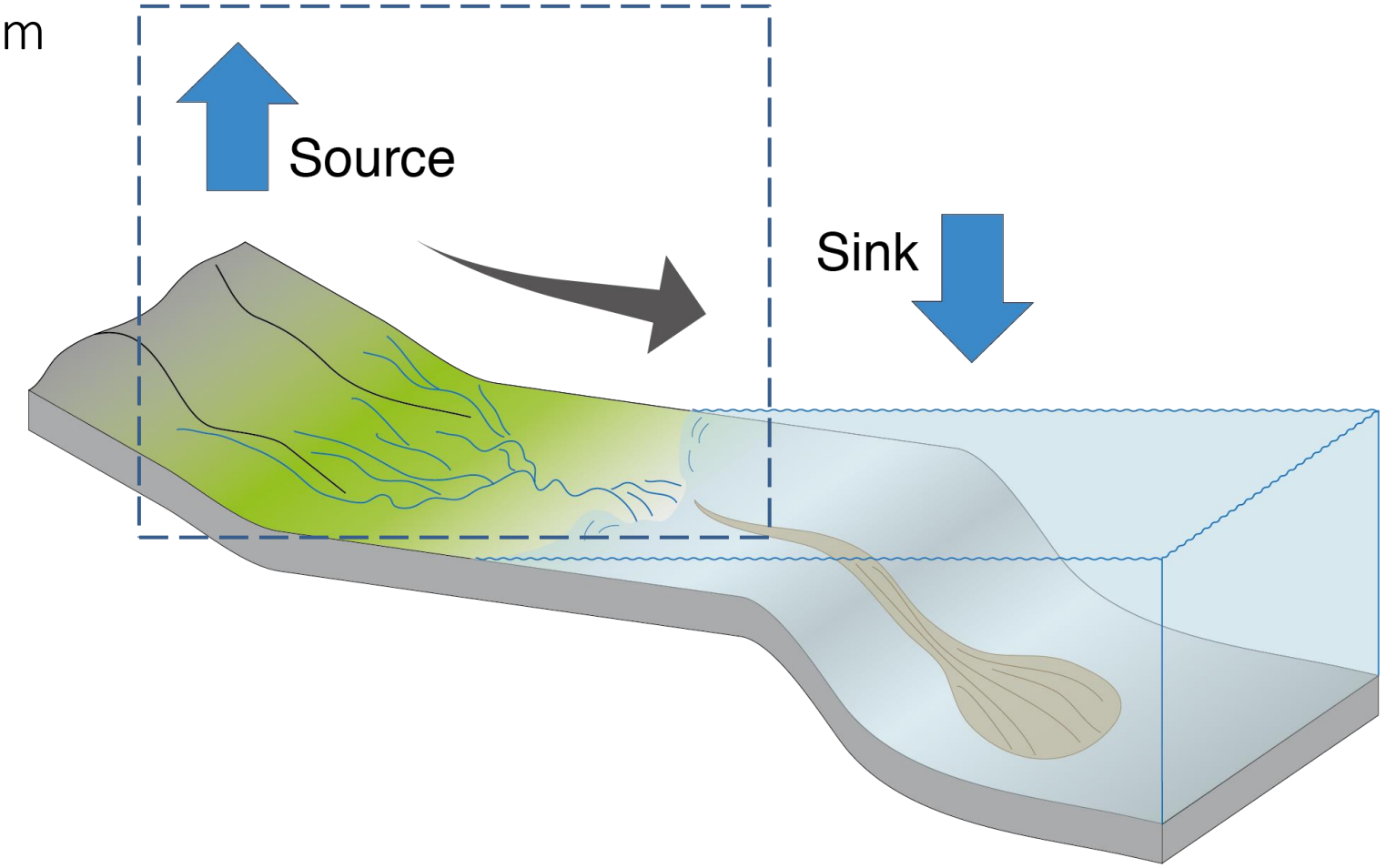
- Source-to-sink/Petroleum system
- Geodynamics

## Knowns

- Wavelength and hinge
- Where and when

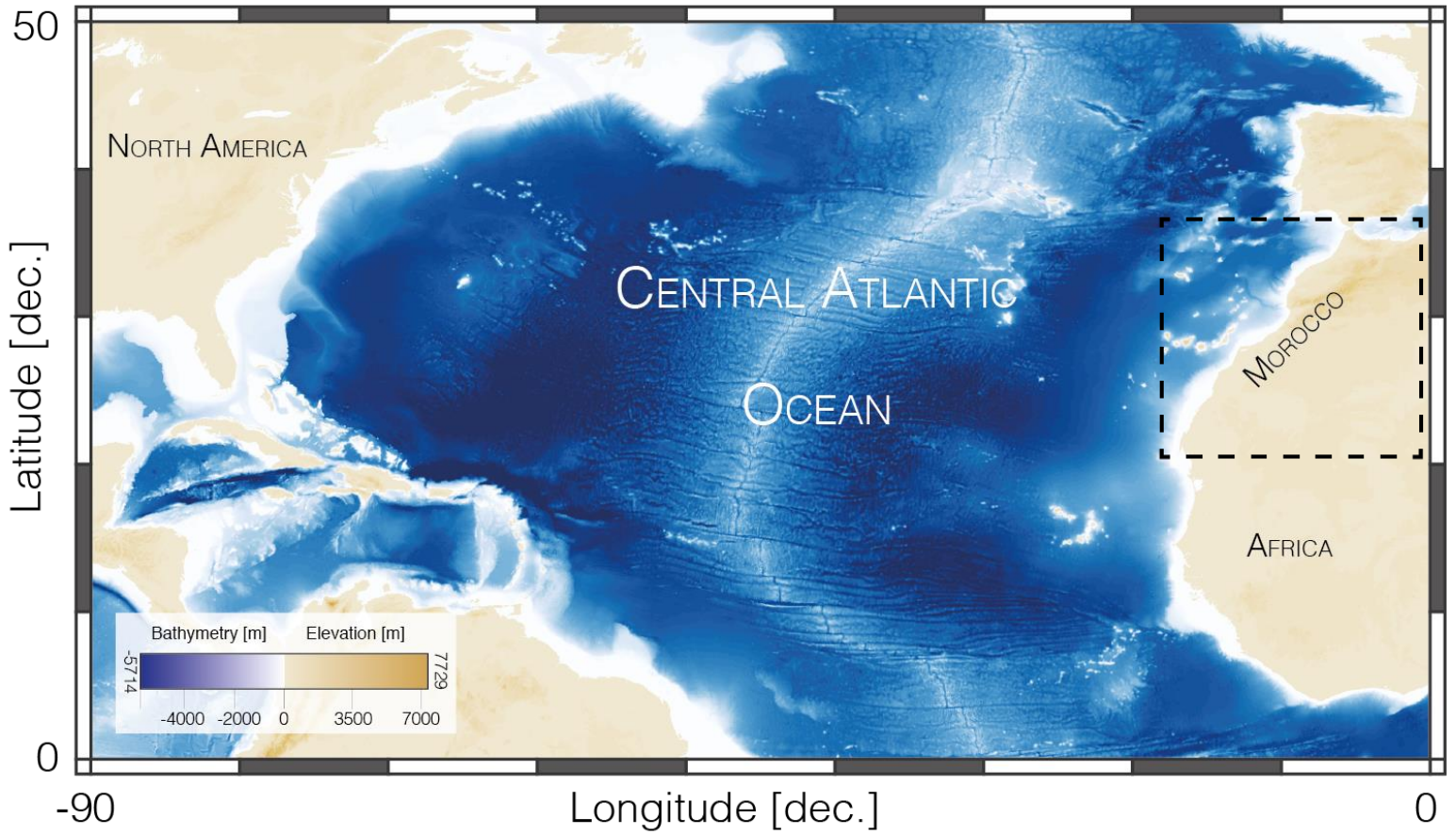
## Unknowns

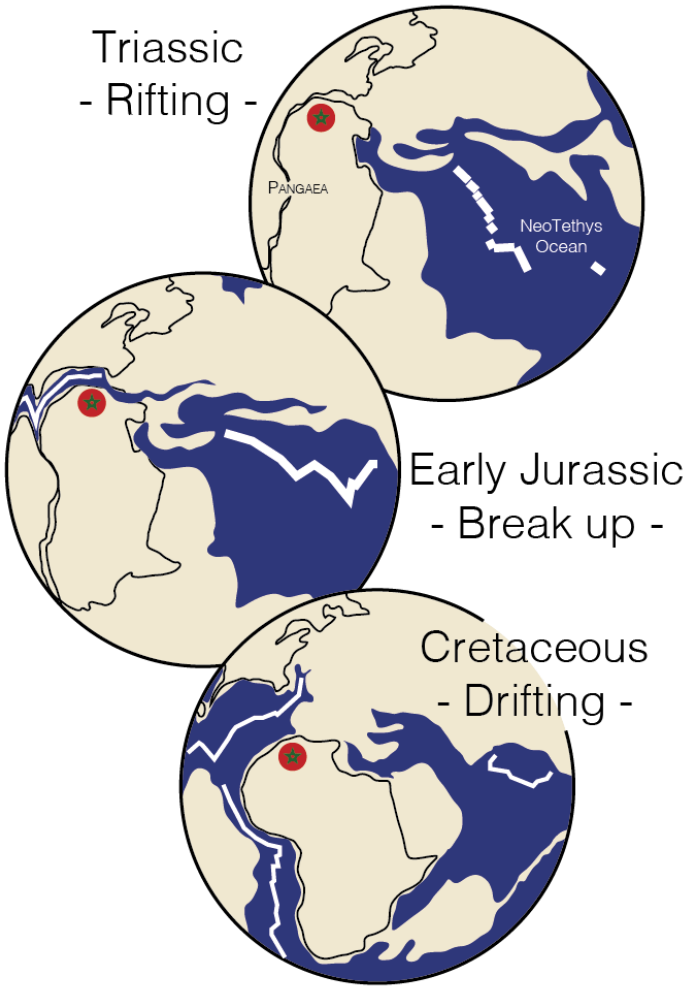
- Rates and volumes?




after Helland-Hansen et al., 2016

# Central Atlantic




after Stampfli and Borel, 2012

Why Morocco?

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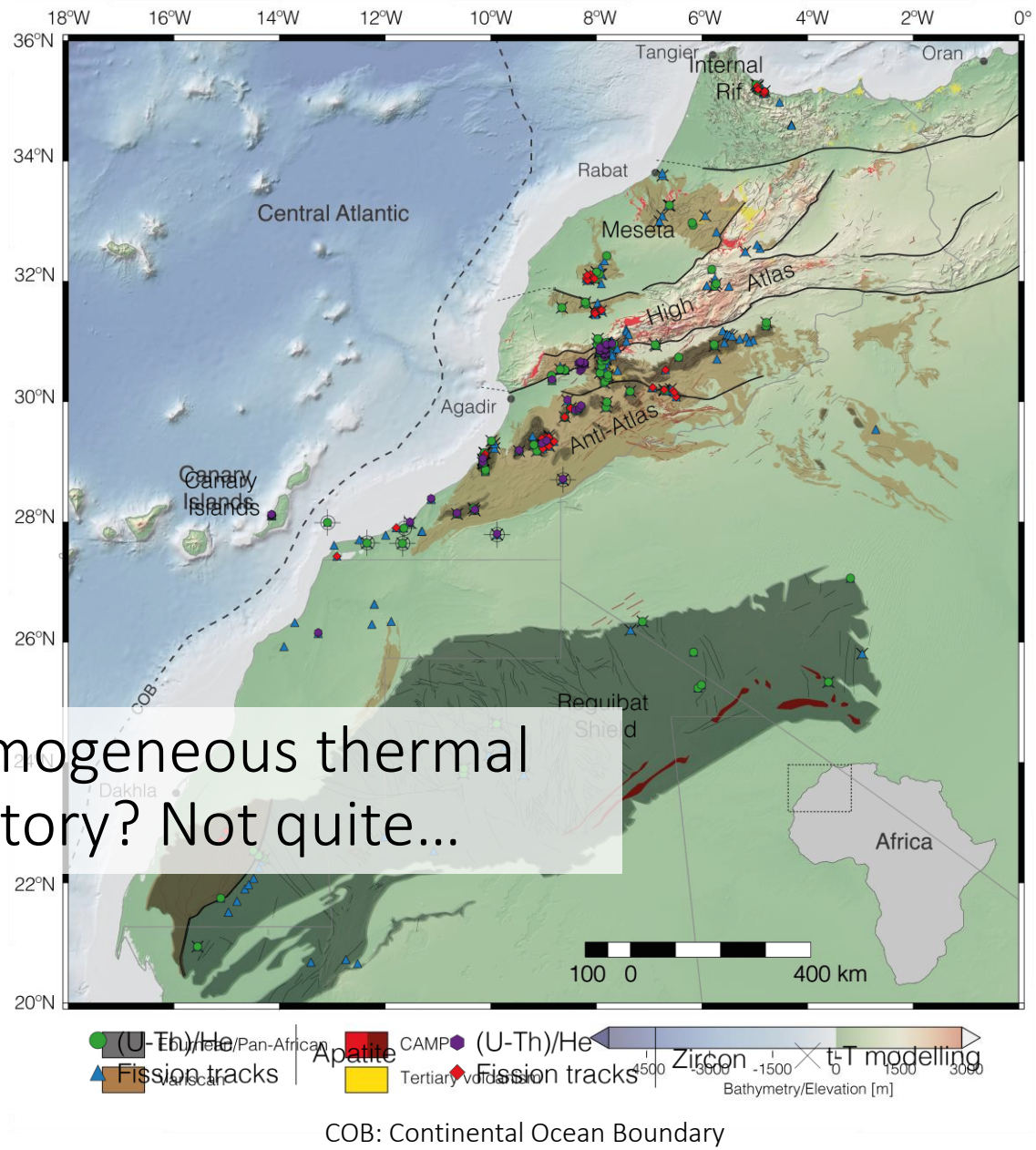
# Low-Temperature Thermochronology

Great exposure




A homogeneous thermal history? Not quite…

A large database

529 AHe
312 AFT
225 ZHe
59 ZFT

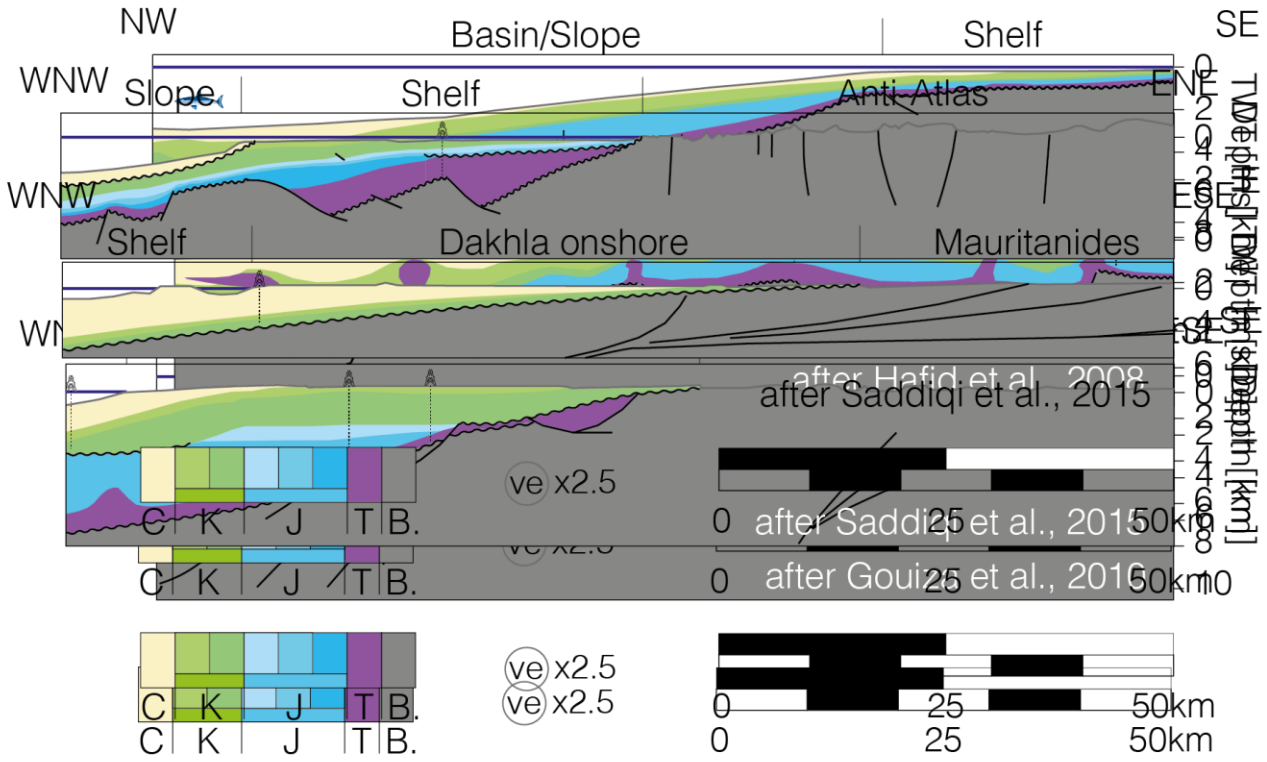
Documenting vertical movements

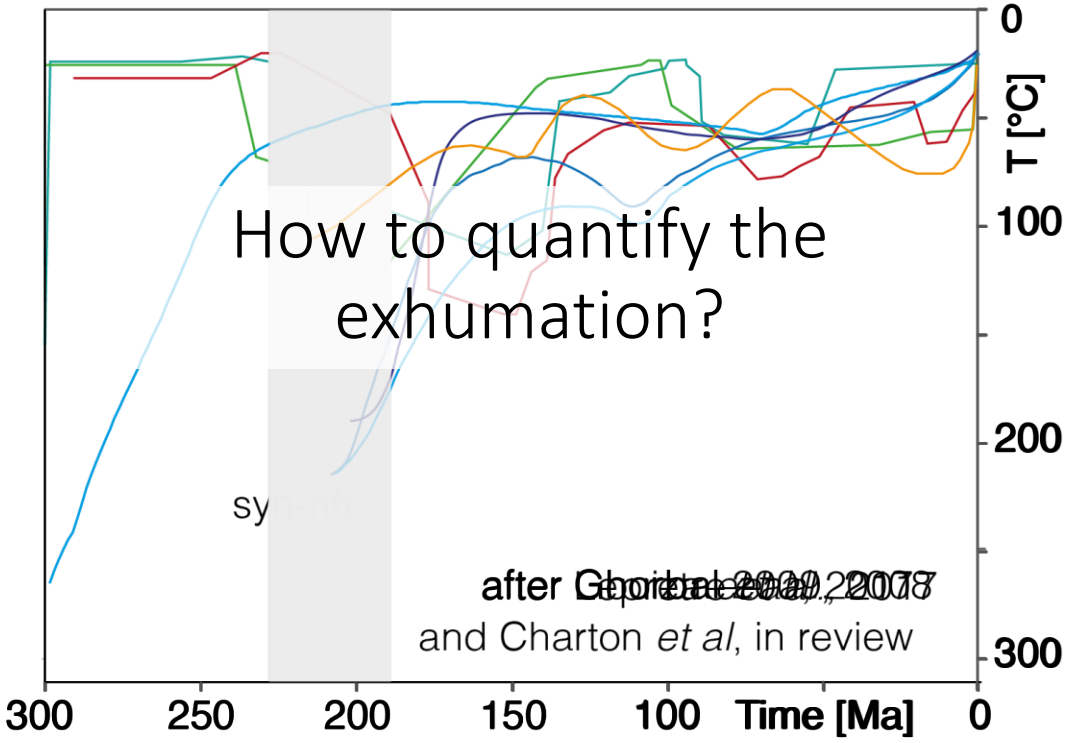
COB: Continental Ocean Boundary

# The Moroccan rifted margin

## Reguibat Shield


Profile and sample location

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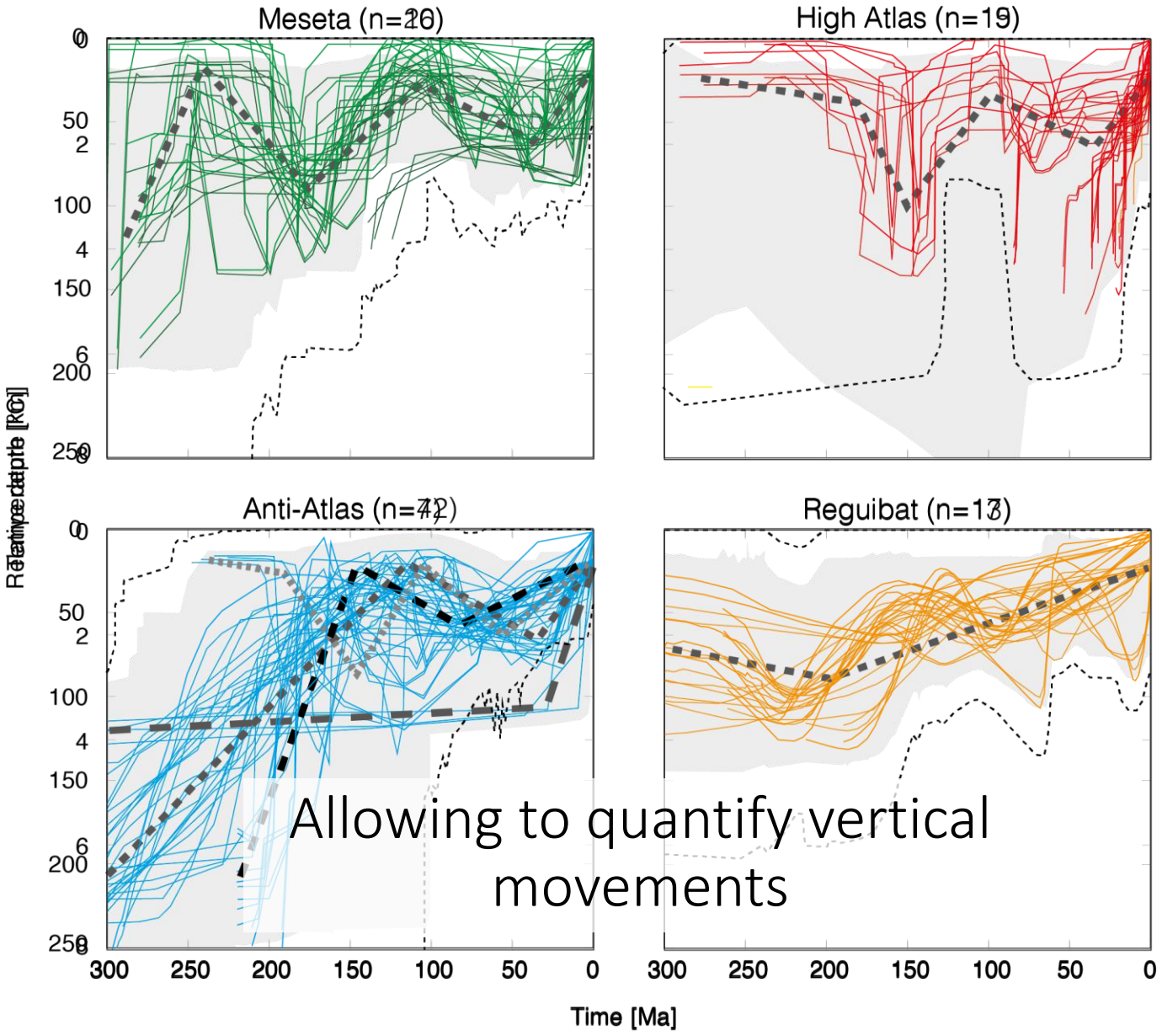
# Time-Temperature modelling … to depth




Allowing to quantify vertical movements

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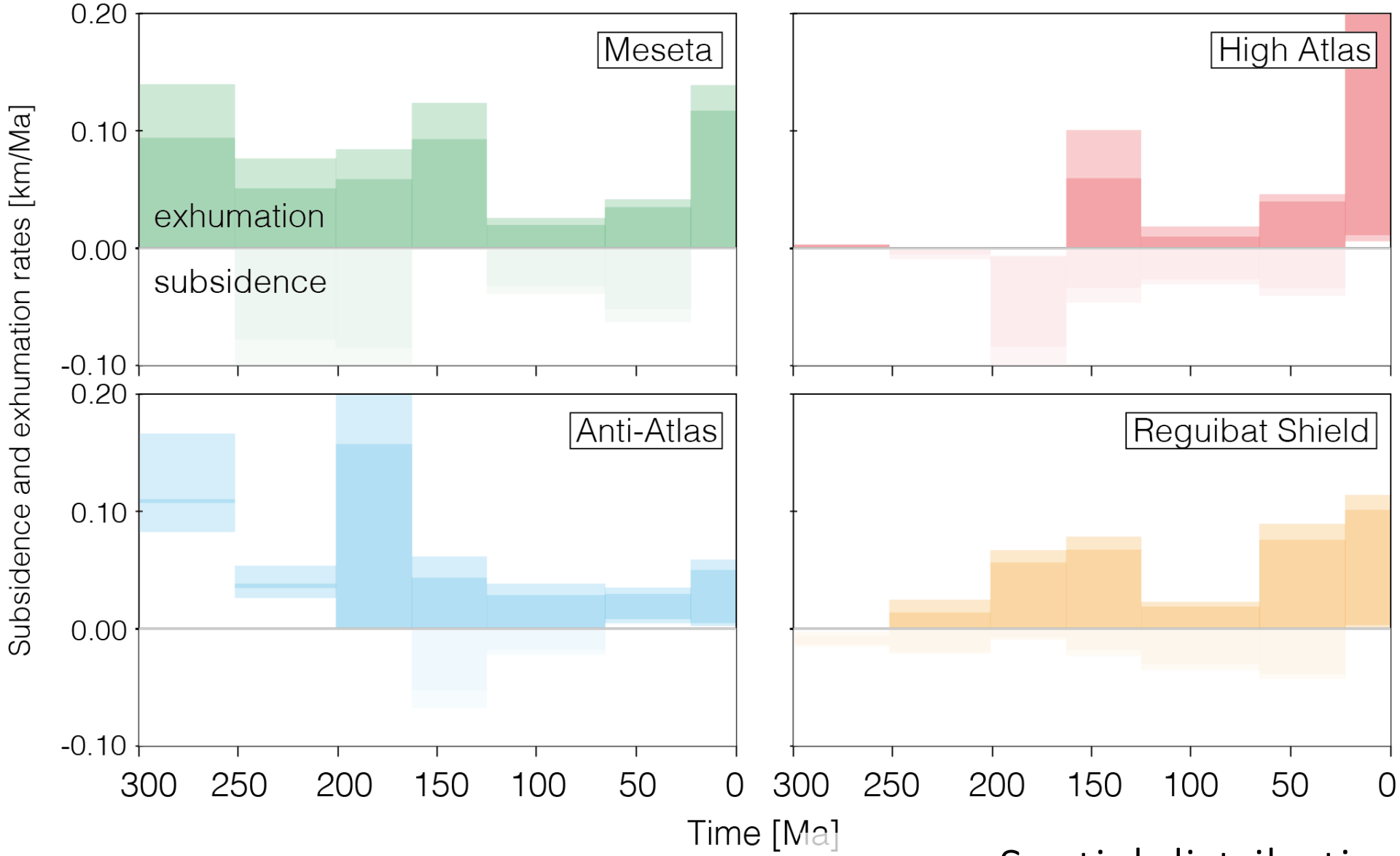
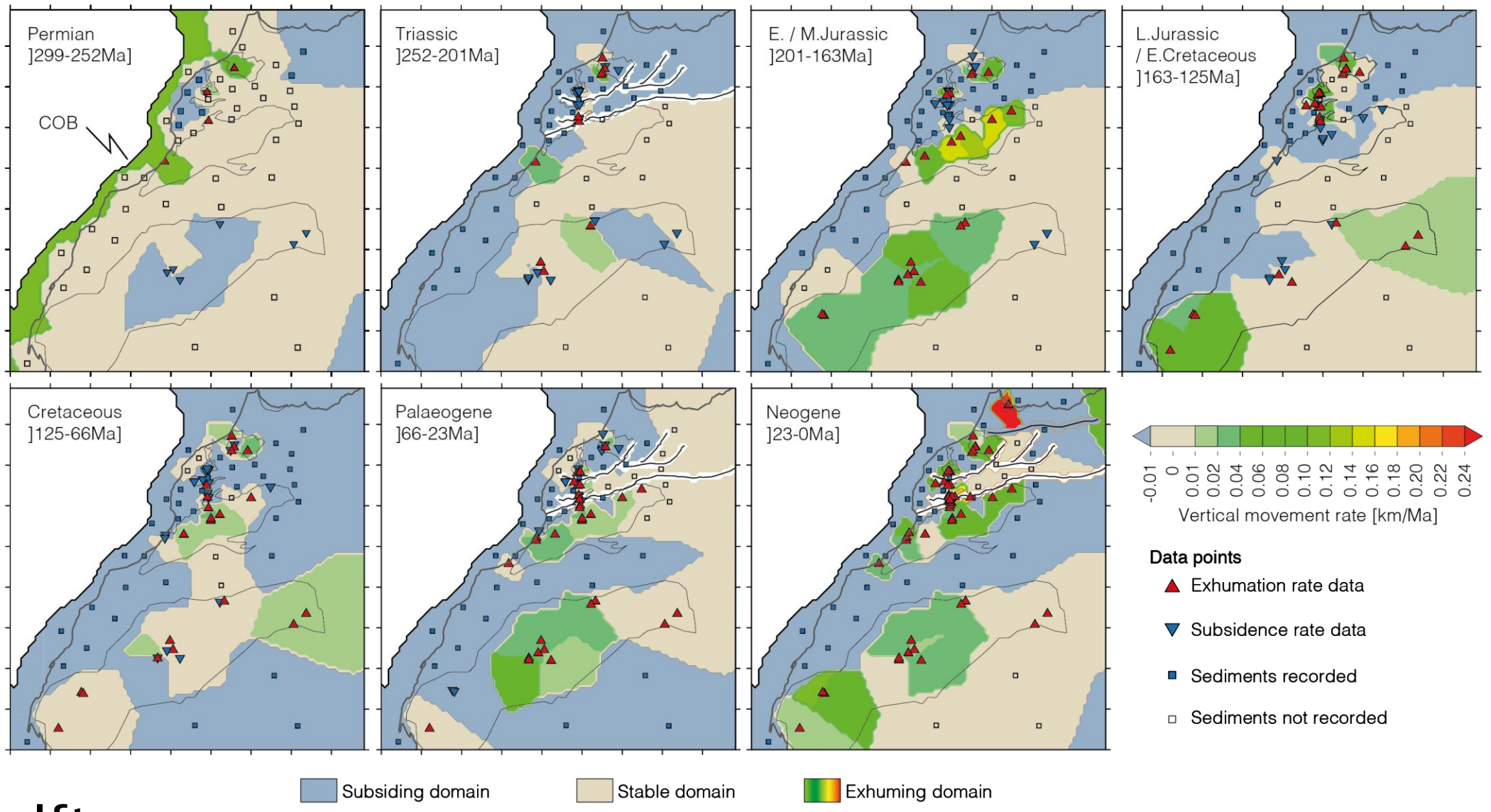
# Vertical movement rates [km/Ma]




Spatial distribution?

# Exhumation maps

## Shifts in source areas?

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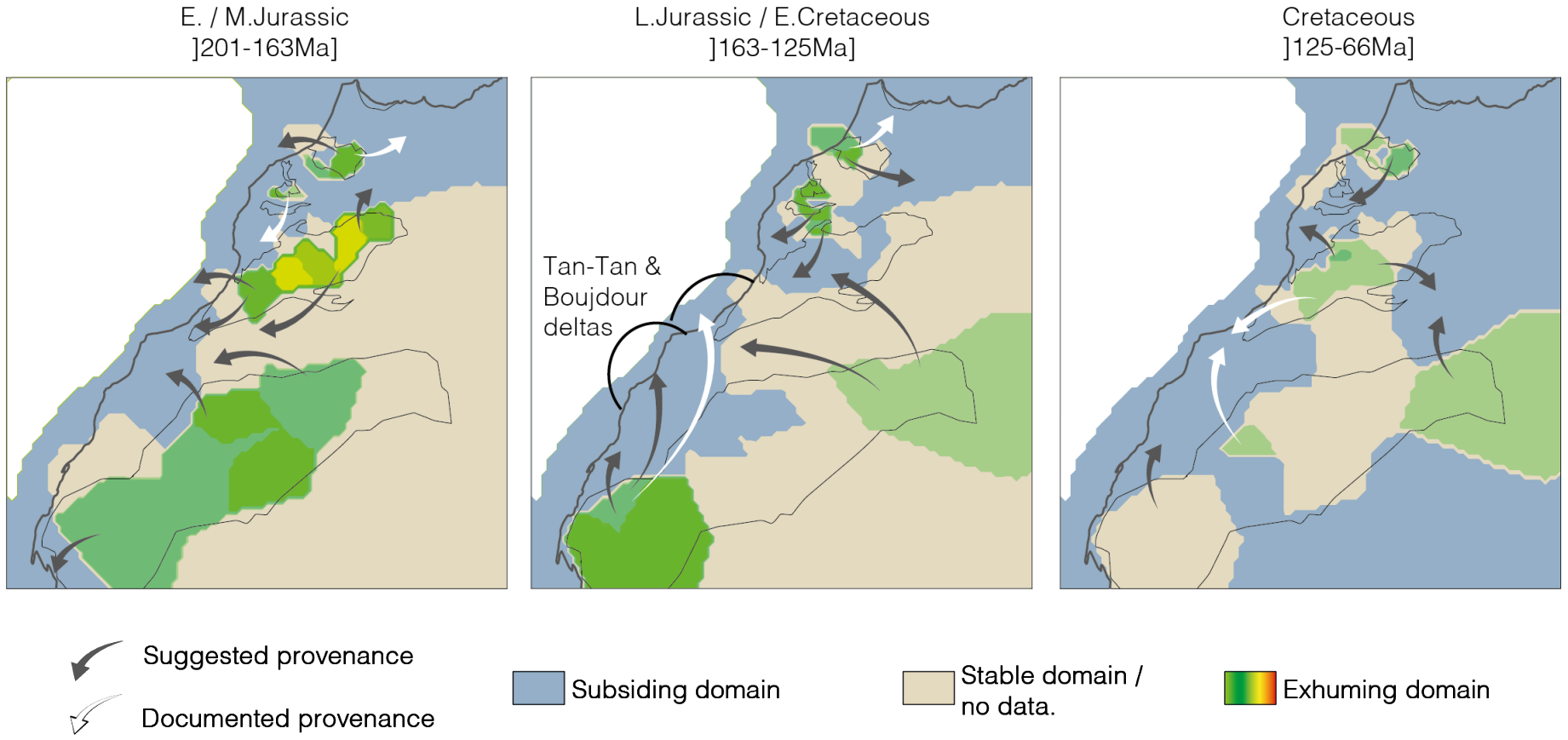
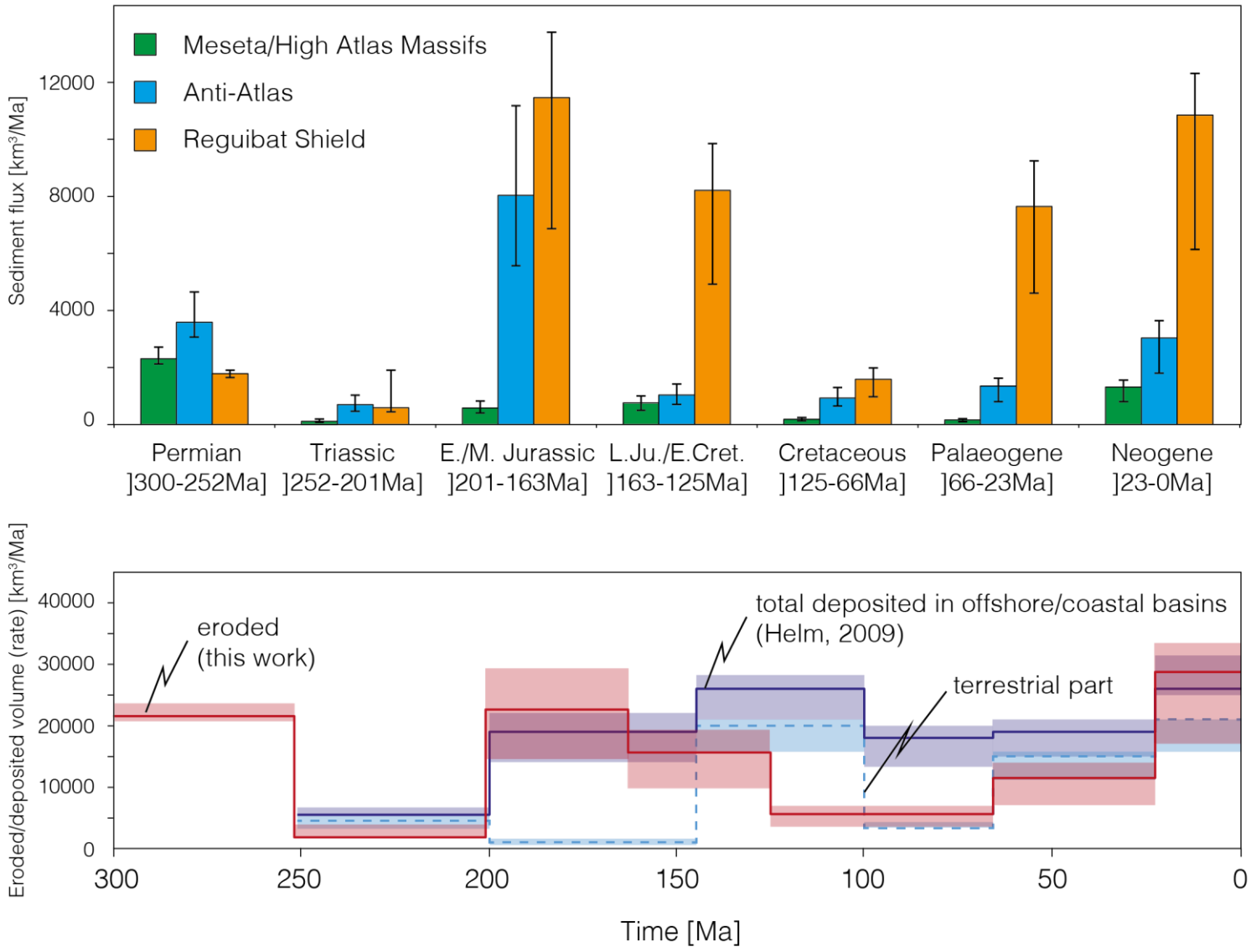
# Implications for source-to-sink systems




How much was eroded?

# Volumes of eroded material per Ma

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# Conclusions

Exhumation…

- patterns mapped for the first time
- rates up to 0.2 km/Ma
- volumes up to 12,000 $km^3$/Ma

Sediment Provenance

- Major **source shifts** in the Jurassic and Cretaceous
- **Cretaceous deltas** sourced from Reguibat only.

# Thank you

Project

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Back-up

*Rates and Volumes*

Geotherms

Temporal distribution of LTT

Stratigraphy

LTT studies

*Wavelength and hinge*

Anti-Atlas sampling

Wavelength of the vertical movements

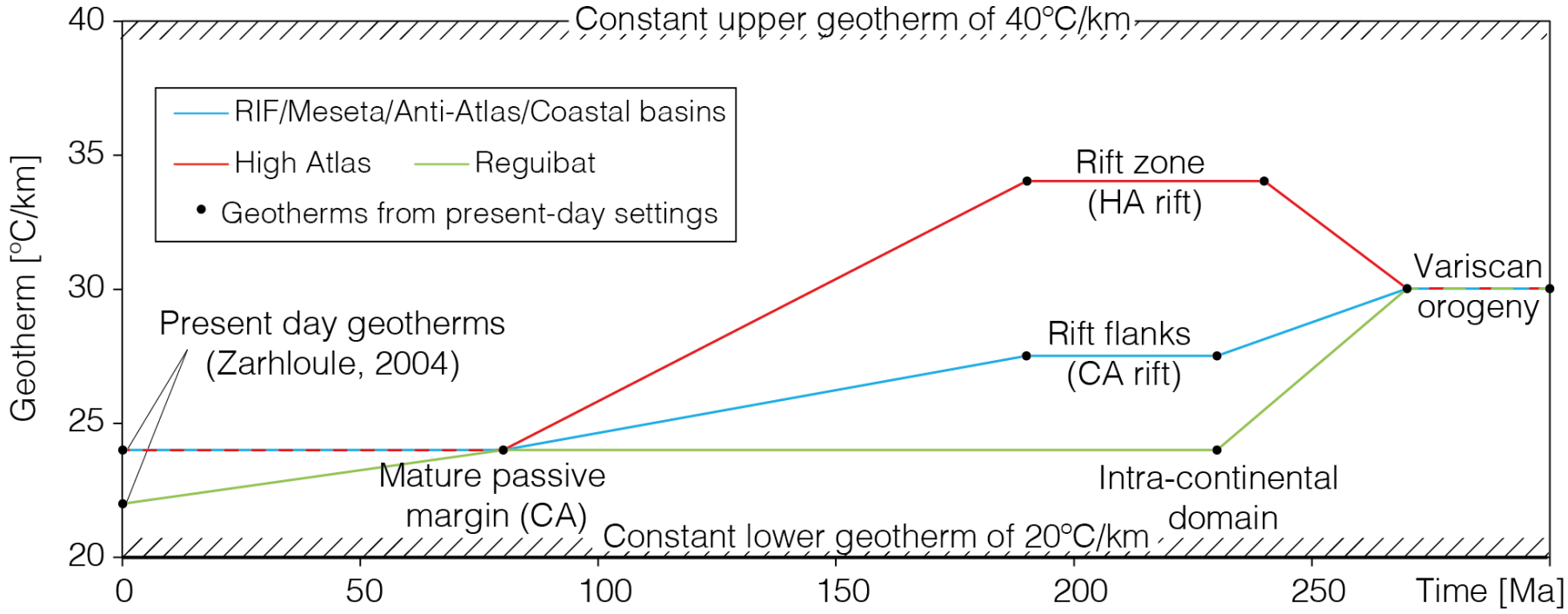
Ifni sampling

Hinge: Evolution of the vertical movements

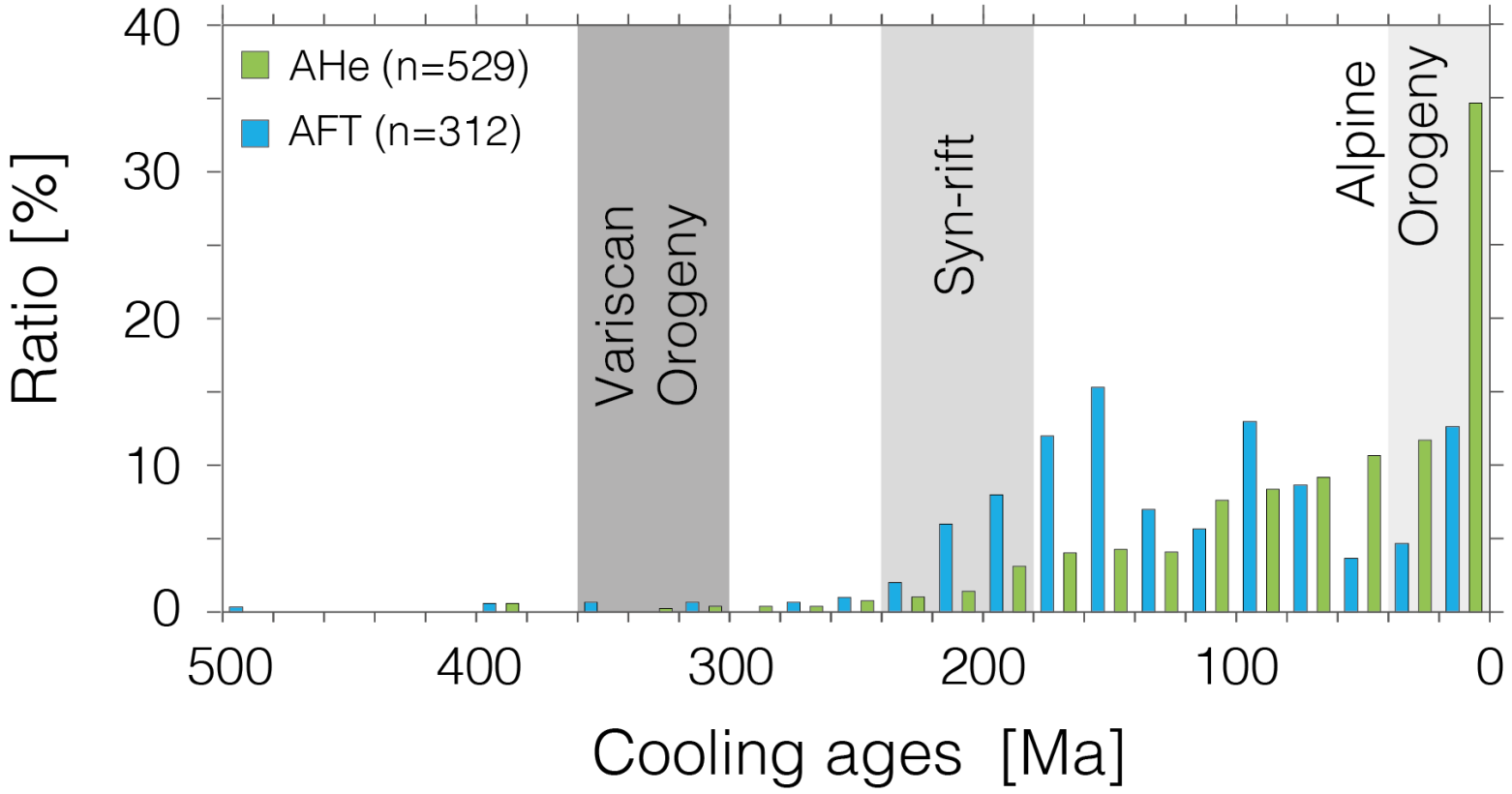
*Mechanisms*

Compilation

# Geotherms


Constant upper geotherm of 40°C/km
RIF/Meseta/Anti-Atlas/Coastal basins
High Atlas
Reguibat
Geotherms from present-day settings
Geotherm [°C/km]
40
35
30
25
20
Rift zone
(HA rift)
Variscan
orogeny
Present day geotherms
(Zarhloule, 2004)
Rift flanks
(CA rift)
Mature passive
margin (CA)
Intra-continental
domain
Constant lower geotherm of 20°C/km
0
50
100
150
200
250
Time [Ma]

# Temporal distribution of LTT

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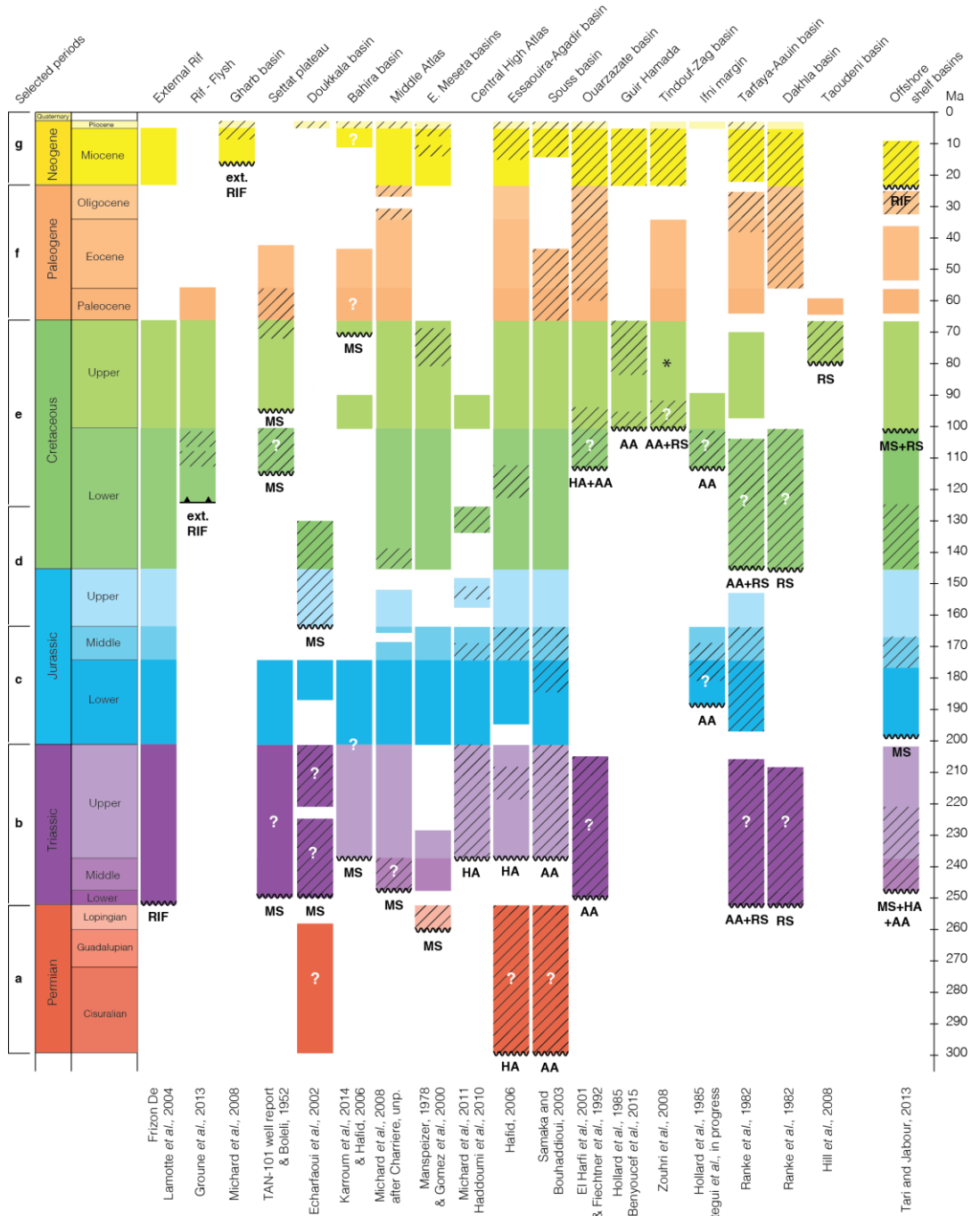
# Simplified stratigraphy of NW Africa basins

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# LTT Studies

| | Locations | References | Stratigraphic age of sample | AHe [Ma] (a/n) | AFT [Ma] (n) | ZHe [Ma] (a/n) | ZFT [Ma] (n) | t-T (n) | t-T modelling Software |
|---|---|---|---|---|---|---|---|---|---|
| Rif | Ketama/ Flysch zones | Azdimousa *et al.*, 1998 | Meso. | - | 13-20 (5) | - | 4 failed χ test | - | - |
| | Internal Zone | Azdimousa *et al.*, 2013 | Pal. | - | 14-17 (13) | - | 19 (4) | 2 | HeFTy |
| | | Romagny *et al.*, 2014 | Pal. | 7-21 (45/11) | - | - | - | 2 | QTQt |
| Canary Islands (Spain) | | Wipf *et al.*, 2010 | Meso.-Ceno. | 15-20 (6/2) | 15-46 (3) | 13-21 (6/3) | 50-59 (3) | - | - |
| Eastern Meseta | | Barbero *et al.*, 2007* | Pal. | - | 270 (1) | - | - | 1 | AFT-Solve |
| | | El Haimer, 2014* | Pal. | - | 174-198 (2) | - | - | - | - |
| Western Meseta | Central Massif | Ghorbal *et al.*, 2008* | Pal. | 51-243 (9/3) | 148 (1) | - | - | 1 | HeFTy |
| | | Barbero *et al.*, 2011 | Pal. | - | 202-239 (7) | - | - | 5 | HeFTy |
| | Rehamna | Sabbil, 1995 | Pal. | - | 81-113 (21) | - | 185-228 (6) | 4 | Gallagher et al. (1993) model |
| | | Ghorbal *et al.*, 2008* | Pal. | 15-253 (21/6) | 143-147 (3) | | | 3 | HeFTy |
| | | Saddiqi *et al.*, 2009* | Pal. | - | 148-153 (4) | - | - | 2 | AFT-Solve |
| | Jebilets | Mansour, 1991 | PЄ-Pal. | - | 170-218 (7) | - | - | - | - |
| | | Ghorbal, 2009* | Pal. | 14-70 (16/4) | 155-163 (3) | | | 3 | HeFTy |
| | | Saddiqi *et al.*, 2009* | Pal. | - | 186-203 (6) | - | - | 2 | AFT-Solve |
| | | El Haimer, 2014* | PЄ-Pal. | - | - | - | 276-313 (5) | - | - |
| High Atlas | Central High Atlas | Barbero *et al.*, 2007* | Meso.-Ceno. | 25-135 (6/3) | 76-242 (6) | - | - | 2 | AFT-Solve |
| | Skoura Massif | Barbero *et al.*, 2007* | Pal. | - | 143 (1) | - | - | - | - |
| | Northern Sub-Atlas | Ghorbal, 2009* | Pal.-Meso. | 14-141 (18/4) | 142-153 (2) | - | - | 2 | HeFTy |
| | | Balestrieri *et al.*, 2009* | Meso. | - | 72-185 (2) | - | - | - | - |
| | Eastern Precambrian MAM (Toubkal/ Oukaimeden) | Missenard *et al.*, 2008* | PЄ | - | 9-27 (10) | - | - | - | - |
| | | Ghorbal, 2009* | PЄ | 9-125 (64/17) | 9-134 (17) | - | - | 14 | HeFTy |
| | | Balestrieri *et al.*, 2009* | PЄ-Pal.-Meso. | - | 20-86 (4) | - | - | - | - |
| | | El Haimer, 2014* | PЄ | 6-12 (6/2) | - | - | - | - | - |
| | | Domenech Verdaguer, 2015* | PЄ | 3-11 (33/11) | - | 20-709 (65/23) | - | 3*** | QTQt |
| | Western Palaeozoic MAM | El Haimer, 2014* | Pal. | 2-9 (8/2) | 65-78 (5) | - | - | 1 | HeFTy |
| | | Domenech Verdaguer, 2015* | Pal.-Meso. | - | - | 66-439 (100/19) | - | - | - |

| | Locations | References | Stratigraphic age of sample | AHe [Ma] (a/n) | AFT [Ma] (n) | ZHe [Ma] (a/n) | ZFT [Ma] (n) | t-T (n) | t-T modelling Software |
|---|---|---|---|---|---|---|---|---|---|
| Anti-Atlas | Western Anti-Atlas (Bas Draa / Ifni / Kerdous / Igherm) | Sebti *et al.*, 2009 | PЄ | - | - | - | 319-358 (10) | - | - |
| | | Ruiz *et al.*, 2011 | PЄ | 58-148 (5/5) | 121-173 (10) | 193-248 (4/4) | - | 5*** | HeFTy |
| | | Sebti, 2011 | PЄ | - | 169-189 (5) | - | - | 4 | HeFTy |
| | | Sehrt, 2014* | PЄ | 49-236 (35/12) | 120-218 (21) | 87-362 (24/8) | 287-331 (8) | 14 | HeFTy |
| | | Sehrt, 2014* (wells) | PЄ-Pal. | - | 9-177 (9) | 59-391 (17/6) | 258-483 (10) | 6 | HeFTy |
| | | Lepretre, 2015* | PЄ | 113-248 (14/1) | - | - | - | 1*** | QTQt |
| | | Gouiza *et al.*, 2017* | PЄ | 67-156 (6/2) | 129-135 (2) | - | - | 1 | HeFTy |
| | | Sehrt *et al.*, 2017 | Same as Sehrt, 2014 | | | | | | |
| | | Charton *et al.*, submitted* | PЄ | 67-173 (5/1) | 206 (1) | - | - | 1 | HeFTy |
| | Central Anti-Atlas (Agadir-Melloul / Zenaga / Siroua / Ouzellarh / Bou Azzer) | Missenard *et al.*, 2008* | PЄ | - | 26-87 (4) | - | - | - | - |
| | | Ghorbal, 2009* | PЄ | 36-152 (24/5) | 96-147 (4) | - | - | 4 | HeFTy |
| | | Balestrieri *et al.*, 2009* | PЄ | - | 66-212 (5) | - | - | 2 | HeFTy |
| | | Oukassou *et al.*, 2013 | PЄ | - | 134-171 (9) | - | 306-340 (6) | 2 | HeFTy |
| | | Lepretre, 2015* | PЄ | 36-143 (4/1) | - | - | - | - | - |
| | | Gouiza *et al.*, 2017* | PЄ | 30-146 (13/4) | 87-98 (5) | - | - | 3 | HeFTy |
| | Eastern Anti Atlas (Saghro / Ougnat) | Malusa *et al.*, 2007 | PЄ-Pal.-Meso. | - | 88-239 (10) | - | - | 3 | HeFTy |
| | | Gouiza *et al.*, 2017* | PЄ | 27-114 (12/4) | 156-213 (4) | - | - | 2 | HeFTy |
| Ougarta (Algeria) | | Akkouche, 2007 | Pal. | - | 175 (1) | - | - | - | - |
| Anti-Atlas Coastal margin | | Sehrt, 2014* | Meso. | 63-142 (2/1) | 176-181 (2) | - | - | 1 | HeFTy |
| | | Charton *et al.*, submitted* | Meso. | 51-140 (5/1) | 214 (1) | - | - | 1 | HeFTy |
| Tarfaya Basin | | Sehrt, 2014* | Meso.-Ceno. | 73-302 (3/1) | 92-237 (17) | 48-1195 (9/3) | 404-585 (5) | 1 | HeFTy |
| | | Sehrt, 2014* (wells) | PЄ-Pal.-Meso.-Ceno. | 0-185 (51/21) | 0-147 (27) | - | - | 2 | HeFTy |
| Reguibat Shield | Western Reguibat Shield | Lepretre, 2015* | PЄ | 14-185 (43/11) | 107-175 (13) | - | - | 3 | QTQt |
| | | Lepretre *et al.*, 2015* | Same as Lepretre, 2015 | | | | | | |
| | | Gouiza *et al.*, in revision | PЄ | 1-119 (12/5) | 45-102 (17) | - | 117-159 (2) | - | - |
| | | Lepretre *et al.*, 2017* | Same as Lepretre, 2015 | | | | | | |
| | Central Reguibat Shield (Mauritania) | Lepretre *et al.*, 2013 | PЄ | 92-149 (5/1) | 139-256 (4) | - | - | 4*** | HeFTy |
| | | Lepretre, 2015* | PЄ | 38-396 (20/3) | 150-202 (4) | - | - | 8*** | QTQt |
| | | Bradley *et al.*, 2015 | PЄ | - | 170 (1) | - | - | - | - |
| | | Lepretre *et al.*, 2017* | Same as Lepretre, 2015 | | | | | | |
| | Eastern Reguibat Shield (Algeria/Mau.) | Lepretre, 2015* | PЄ | 32-384 (38/6) | 237-497 (8) | - | - | 2 | QTQt |
| | | Lepretre *et al.*, 2017* | Same as Lepretre, 2015 | | | | | | |
| Taoudeni Basin | | Martín-Monge *et al.*, 2016 | PЄ-Pal. | - | 106-397** (5) | - | - | - | - |

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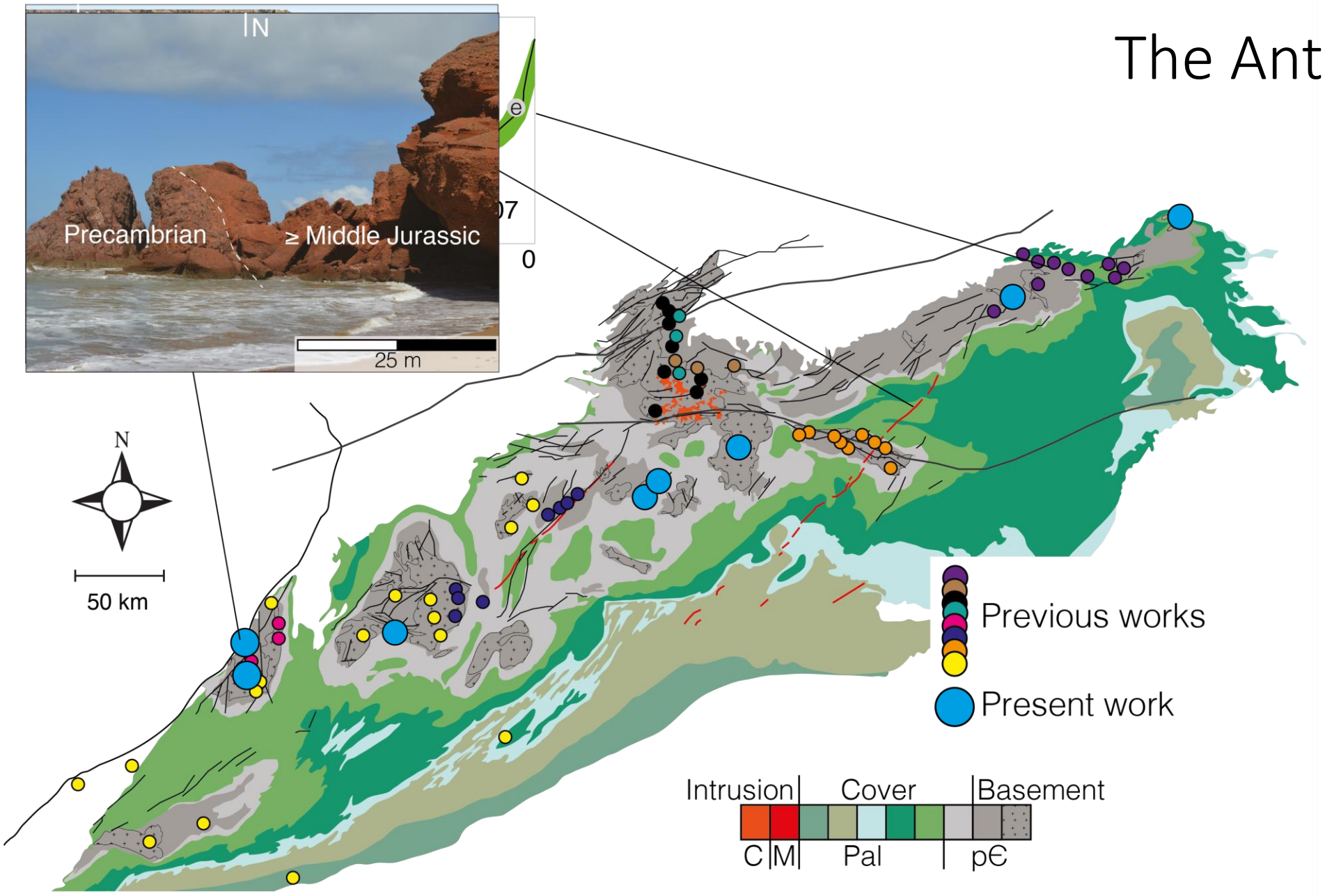
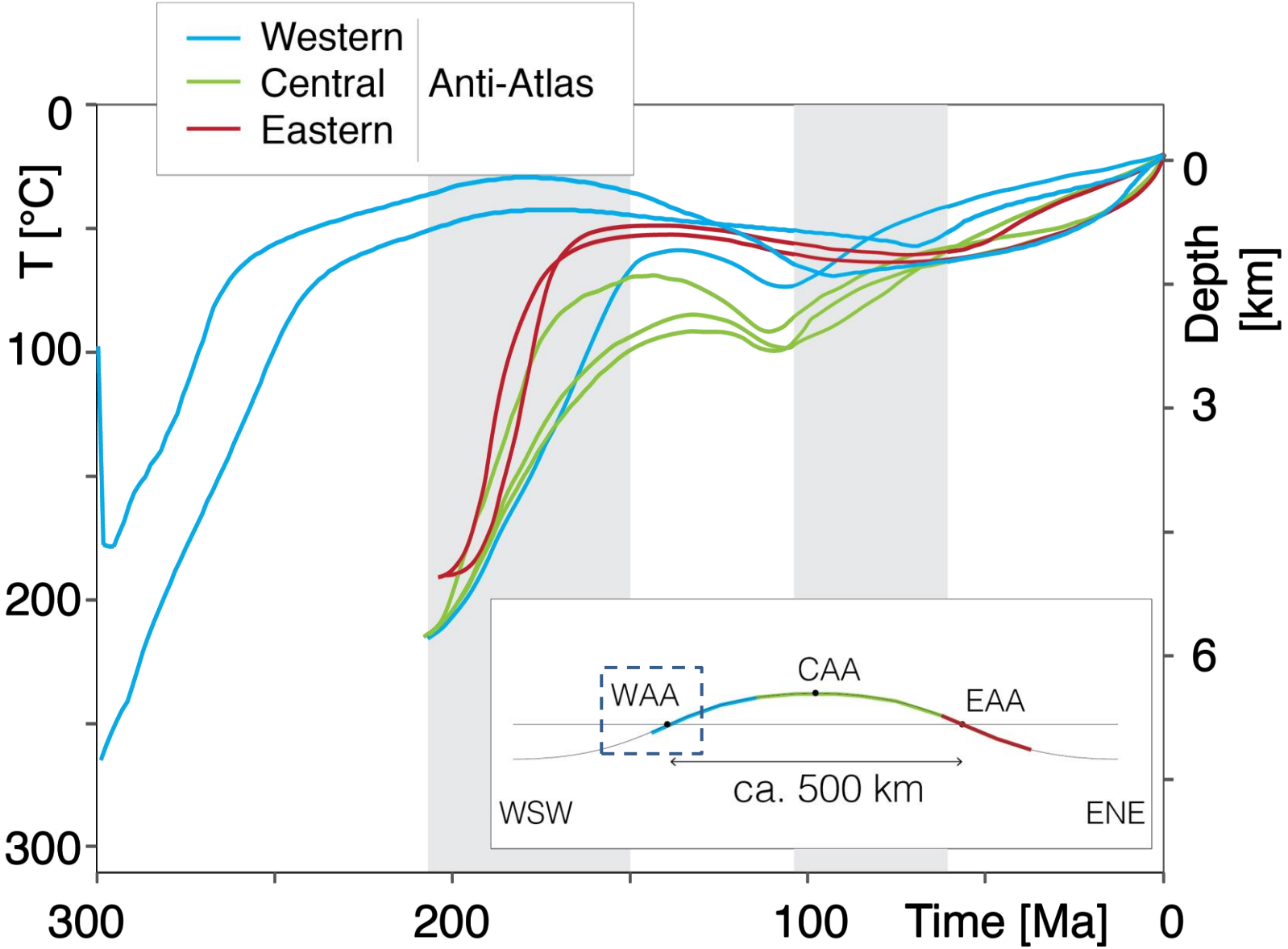
# The Anti-Atlas




Simplified from the geological map (1985)

# Exhumation wavelength(s)

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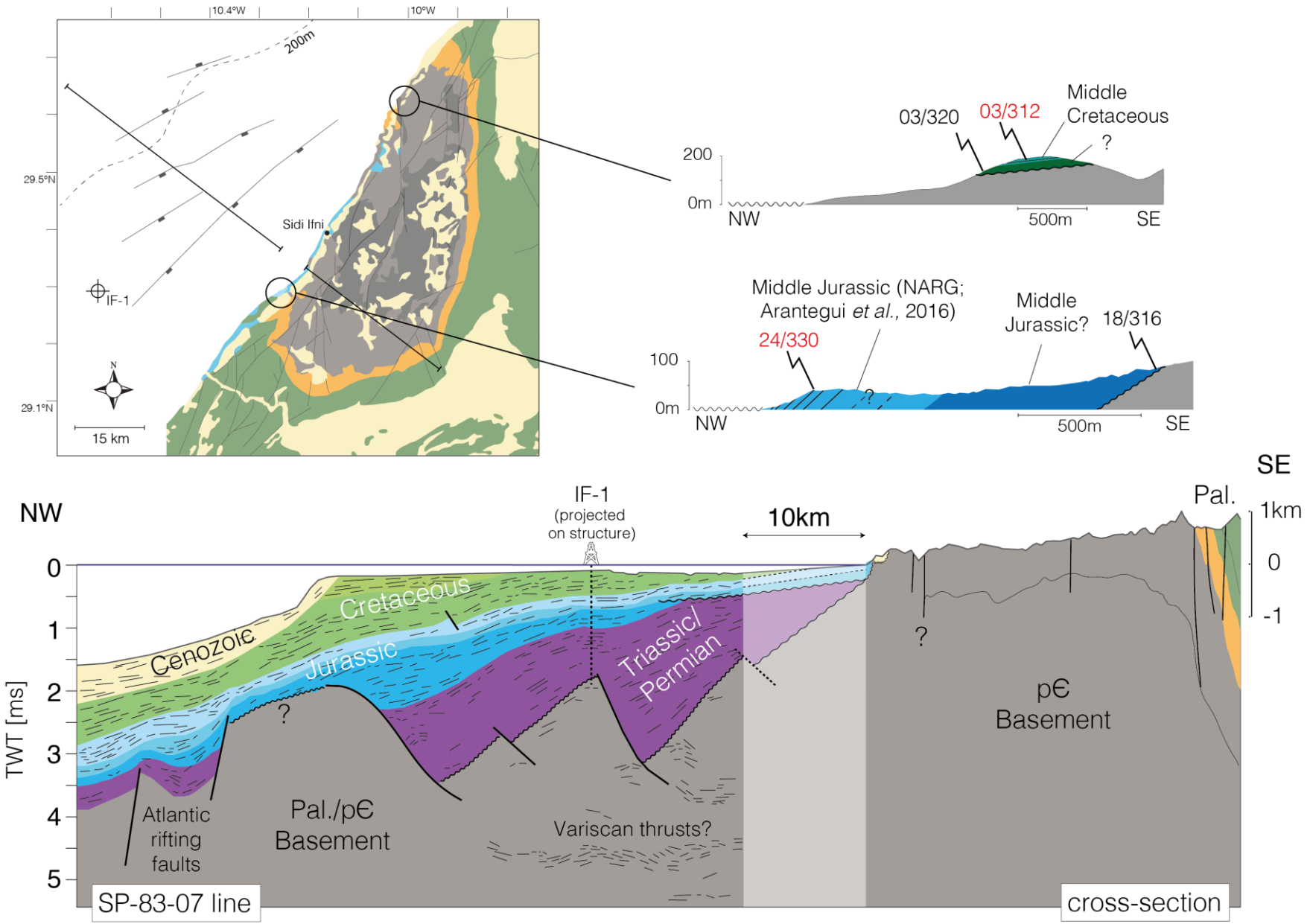
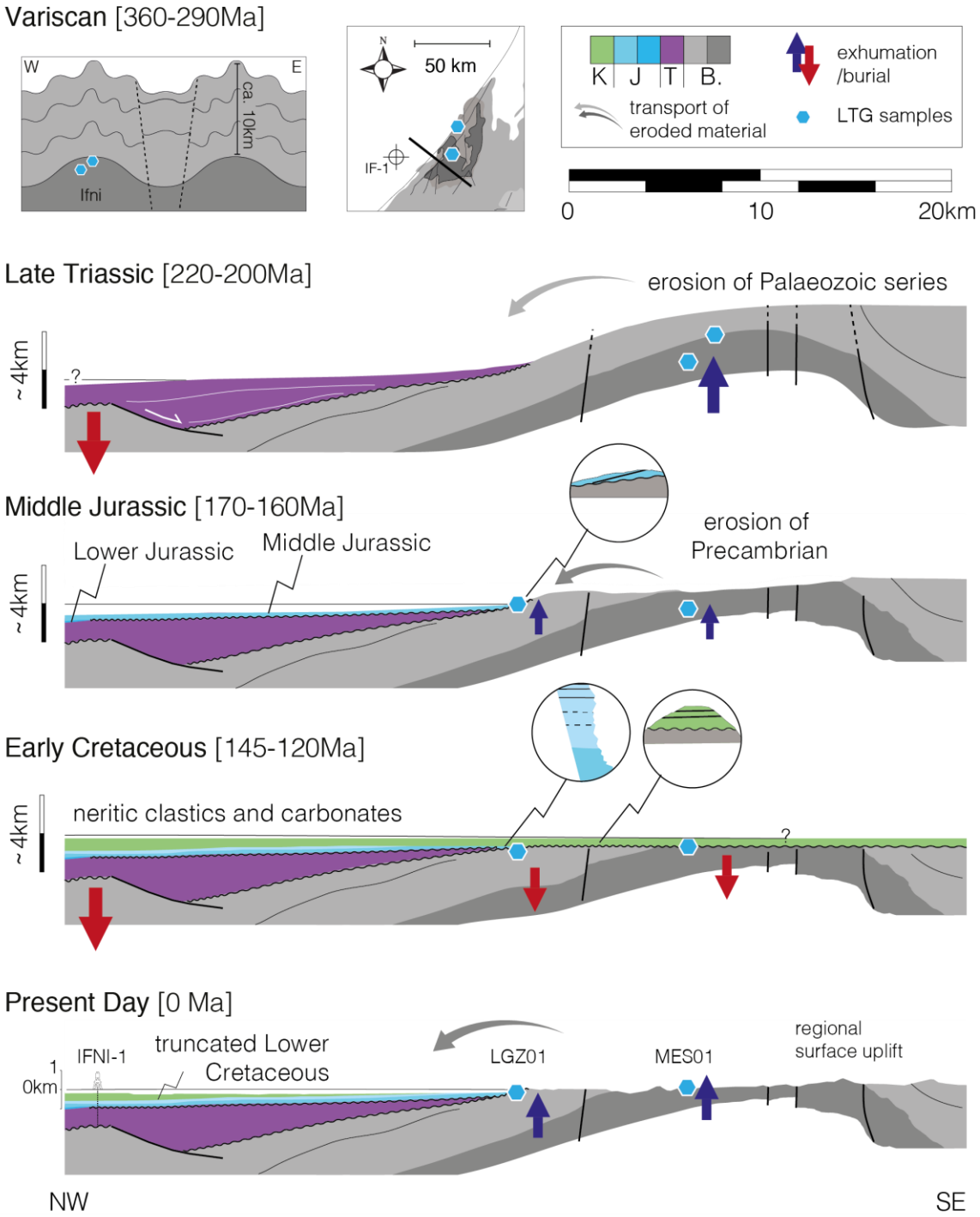
# The Ifni area




after Gouiza, 2011

BACK

# The Ifni transect

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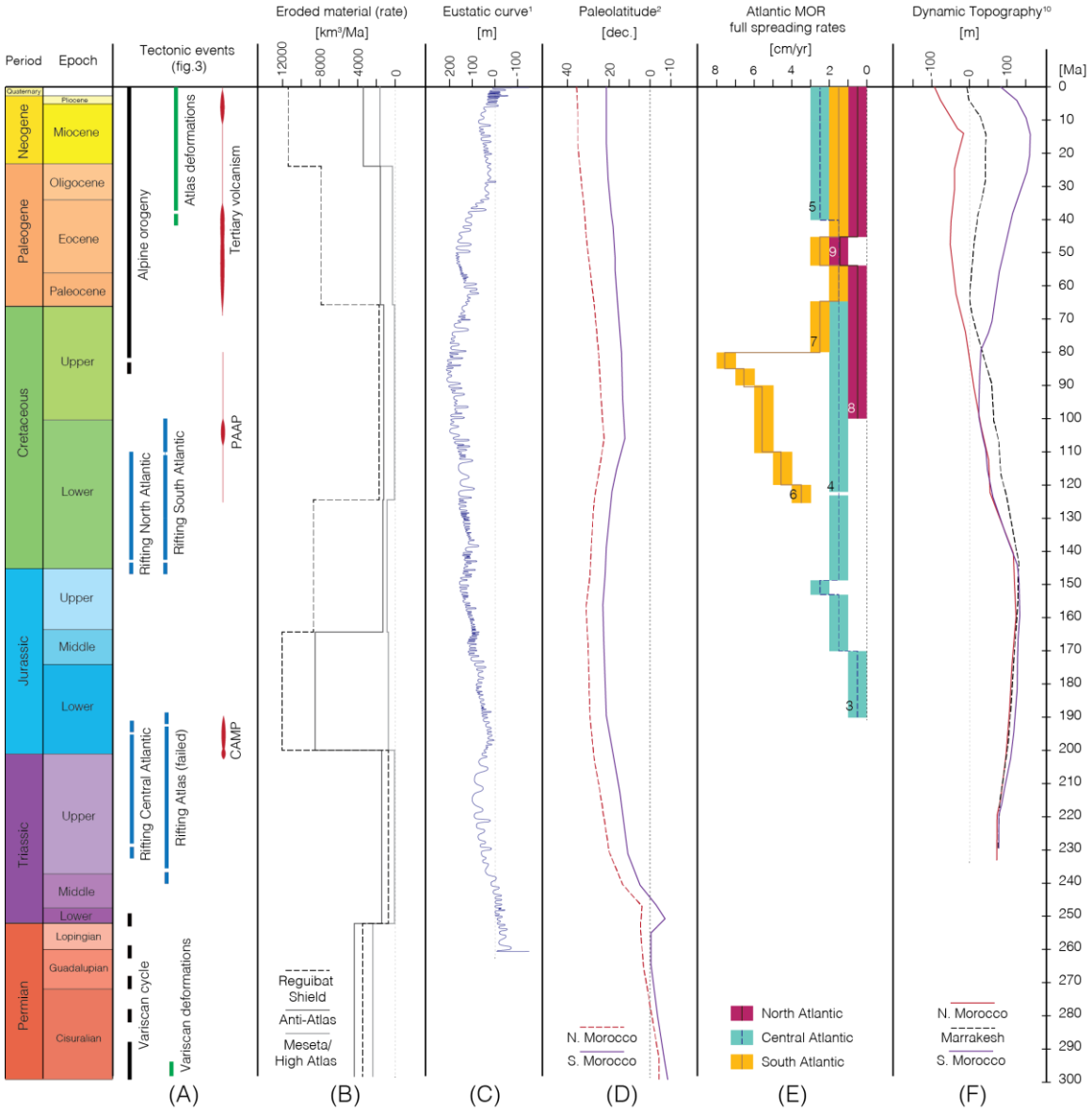
# Mechanisms

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