Evidence for an Early and Sustained Mode of Diffuse Lithospheric Extension in the Central Arabian Rift Flank of the Red Sea Rift System*

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Abstract

The Red Sea Rift (RSR) exhibits dissimilar rift character along-strike; sea-floor spreading has operated in the southern Red Sea since ~5 Ma while the continental lithosphere has not ruptured in the central and northern sections. To explore this contrast, we use apatite and zircon (U-Th)/He thermochronology and MATLAB-based modeling techniques to establish the time-temperature (t-T) history of extended continental lithosphere within the central Arabian rift flank (CARF). Trends in our (U-Th)/He age database identify multi-scale structural domains that accommodated diffuse extension within the CARF and controlled rift flank architecture with progressive rifting. Thermal modeling reveals a three-stage thermotectonic t-T history for the region. The Arabian-Nubian Shield experienced a Paleo-Mesozoic cooling event that brought the CARF terrane to a mid-to-upper crustal structural level where it remained thermally stable through the Mesozoic. With the onset of rifting, the CARF terrane was dissected and exhumed along numerous rift-parallel fault blocks from pre-rift flank depths of ~1.5 - 3.9 km. Minimal reheating paths in our models indicate the absence of common reheating mechanisms such as burial by significant accumulations of pre-rift volcanic or Paleo-Mesozoic sedimentary overburden thicknesses and/or increased heat flow in mid-to-upper-crustal levels from active rifting processes. Rifting in the CARF began with the onset of major extension ca. 23 Ma. This rift signal is mirrored elsewhere along the Red Sea Nubian margin and the southern Arabian rift flank in Saudi Arabia and Yemen, confirming that Red Sea rifting began concomitantly along the near-full length of the Red Sea - Gulf of Suez system. Since this time, block faulting, as opposed to rigid, regional flank uplift has been the dominant structural style in the

CARF. Highly segmented rift flank dissection and widespread fault block exhumation, including synchronous development of the intra-marginal Hamd and Jizil half-grabens, created a ~200 km-wide zone of diffuse extension that endured for ~8 million years. Inboard RSR deformation begins near the coincident intersection of the Makkah-Medina-Nafud volcanic line with the Red Sea axial trough at 21° north latitude and expands to the northwest where it encompasses pre- and syn-rift grabens (e.g., Azlam and Tabuk) and defines a "deformed wedge" of diffuse continental lithosphere extension, altogether different from the relatively rigid southern Arabian margin.

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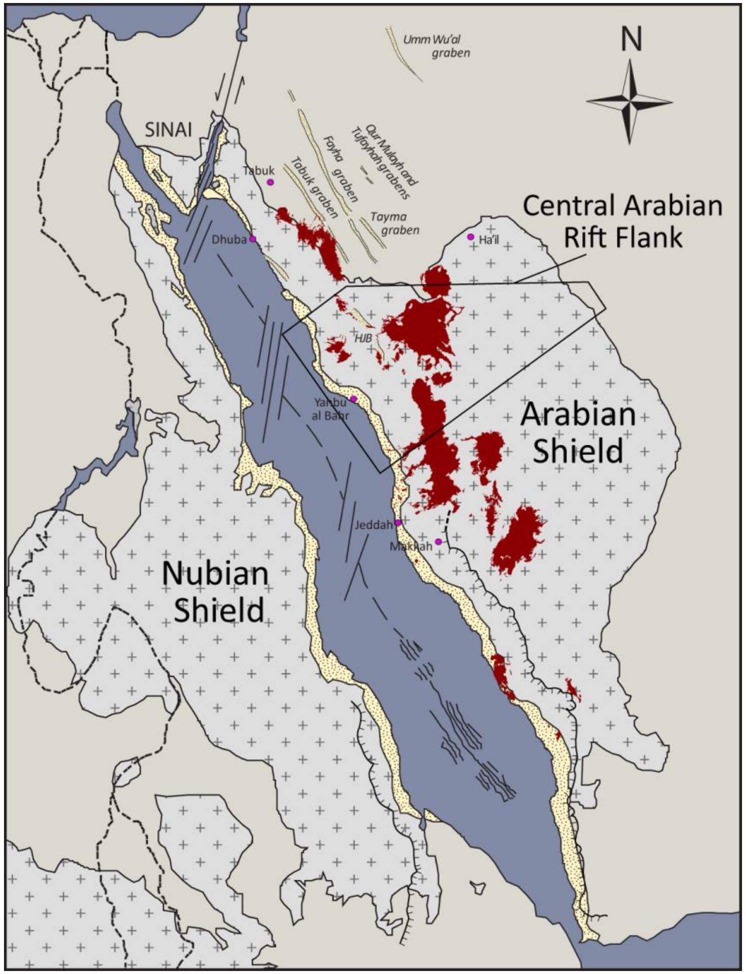
KEY ISSUES

- Central and northern RSR continental lithosphere has not ruptured
- What controls the along-strike change in rift flank volcanic and structural elements? (escarpment, harrat)

KEY RESULTS

- Onset of RSR began concomitantly along the near-full length of the Red Sea – Gulf of Suez system ~23 Ma
- Structural style fundamentally different between the southern and central / northern Arabian rift flank
  - diffuse deformation: CARF subdivided into two primary structural domains (HFC and HJB)
  - 200 km-wide zone of diffuse extension in the CARF endured for ~8 million years
  - CARF fault blocks exhumed along numerous rift-parallel footwalls from pre-rift flank depths of ~1.5 – 3.9 km



Arabian - Nubian Shield
Paleo-Mesozoic Sedimentary and Volcanic Cover
Cenozoic Sedimentary Deposits
Cenozoic basalt
Cenozoic grabens
RSR axial trace
RSR transfer zones
Oceanic Crust

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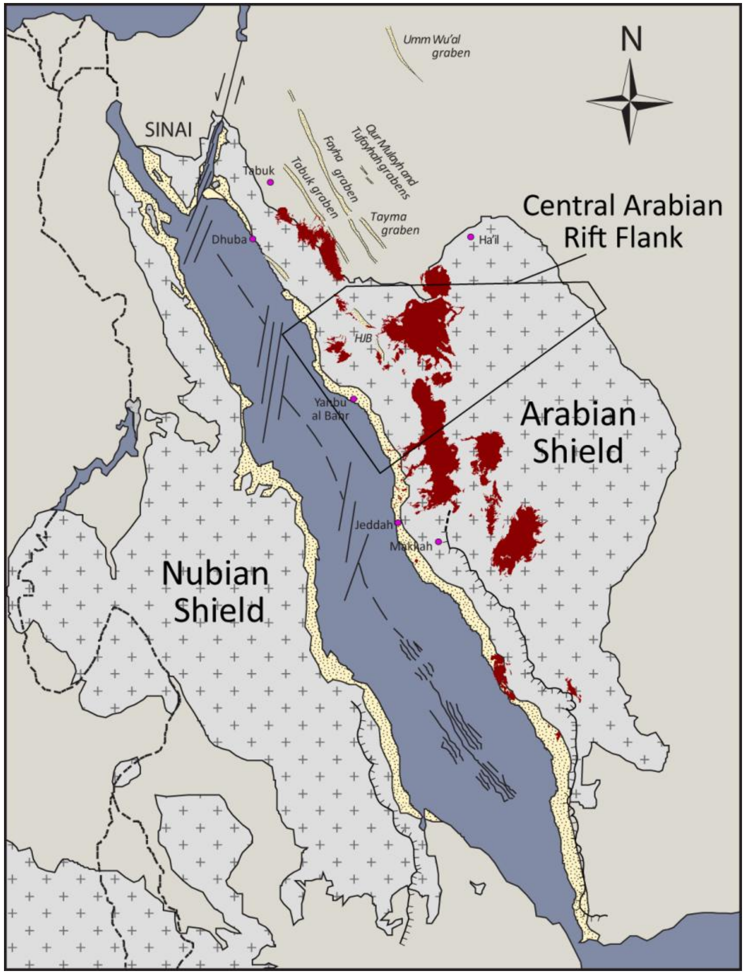
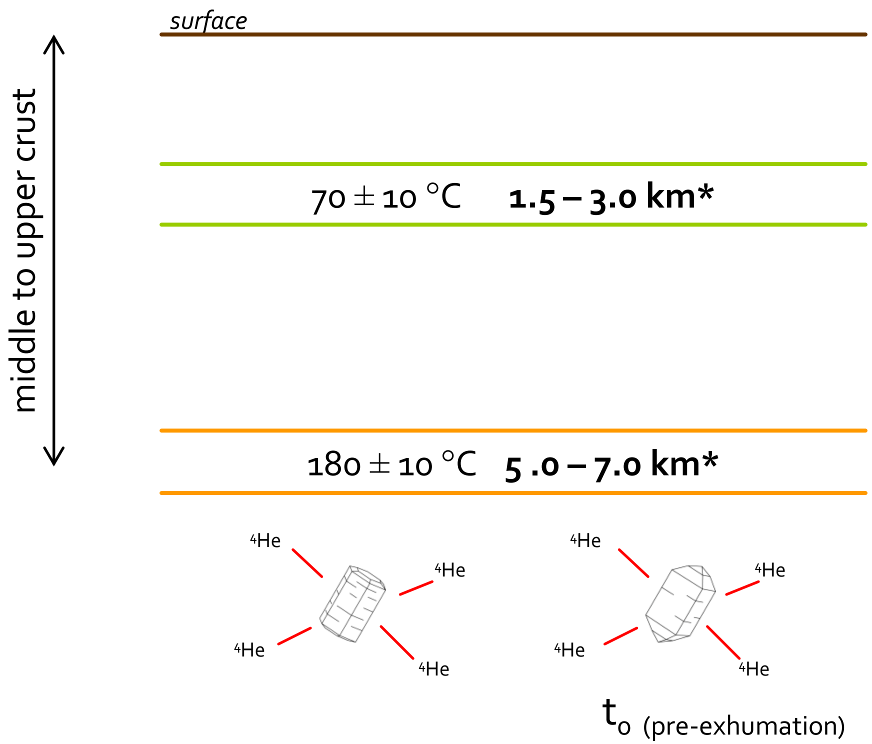
TOPIC OUTLINE

- Apatite and zircon (U-Th)/He thermochronometry in extended regions
- Bedrock AHe, ZHe and Detrital AHe age Results
- t-T modeling Results
  - paleo-geothermal gradient in central nascent RSR
  - CARF exhumation timing and magnitude estimates
- Wrap-up

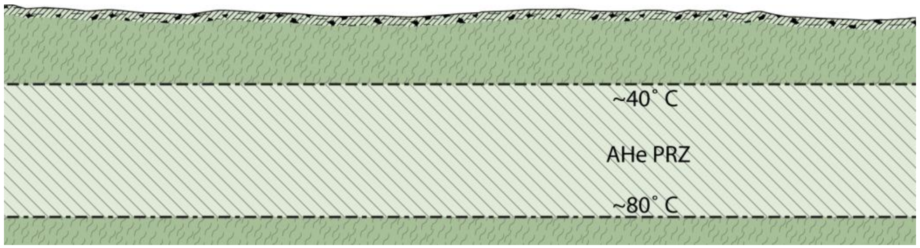


Primer: Low-T (U-Th)/He Thermochronology in Extended Terrane



Pre-existing, stable, geothermal gradient

Ap, Zr losing ^{4}He



**Assuming average 25 °C/km geothermal gradient and average surface T = 25 °C.*

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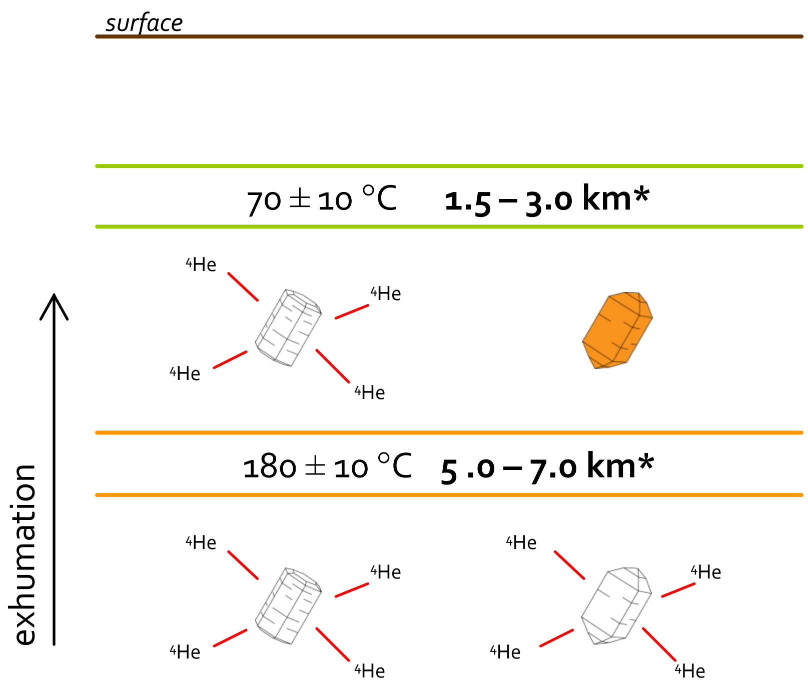
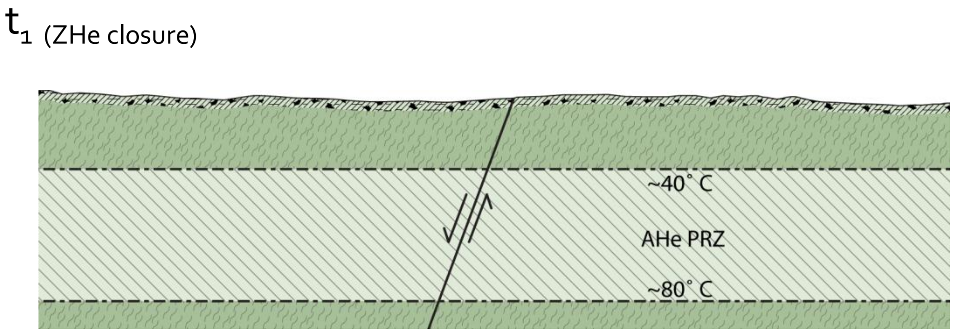


Initiation of extension, rapid footwall exhumation

Ap, Zr begin to cool

Quantitative retention of ^{4}He in Zr

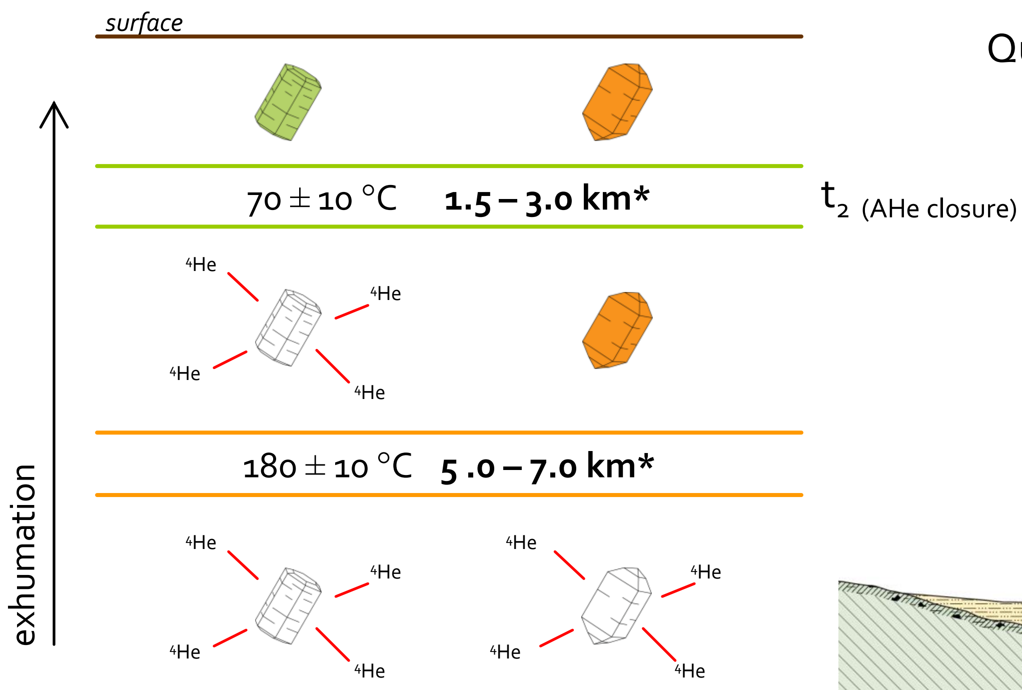


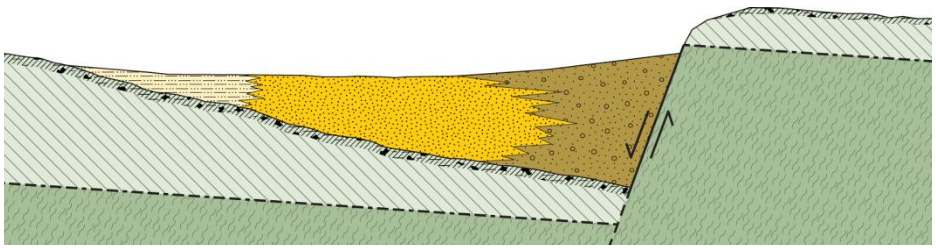
**Assuming average 25 °C/km geothermal gradient and average surface T = 25 °C.*

Primer: Low-T (U-Th)/He Thermochronology in Extended Terrane

Continued rapid footwall exhumation

Quantitative retention of ^{4}He in Ap, Zr





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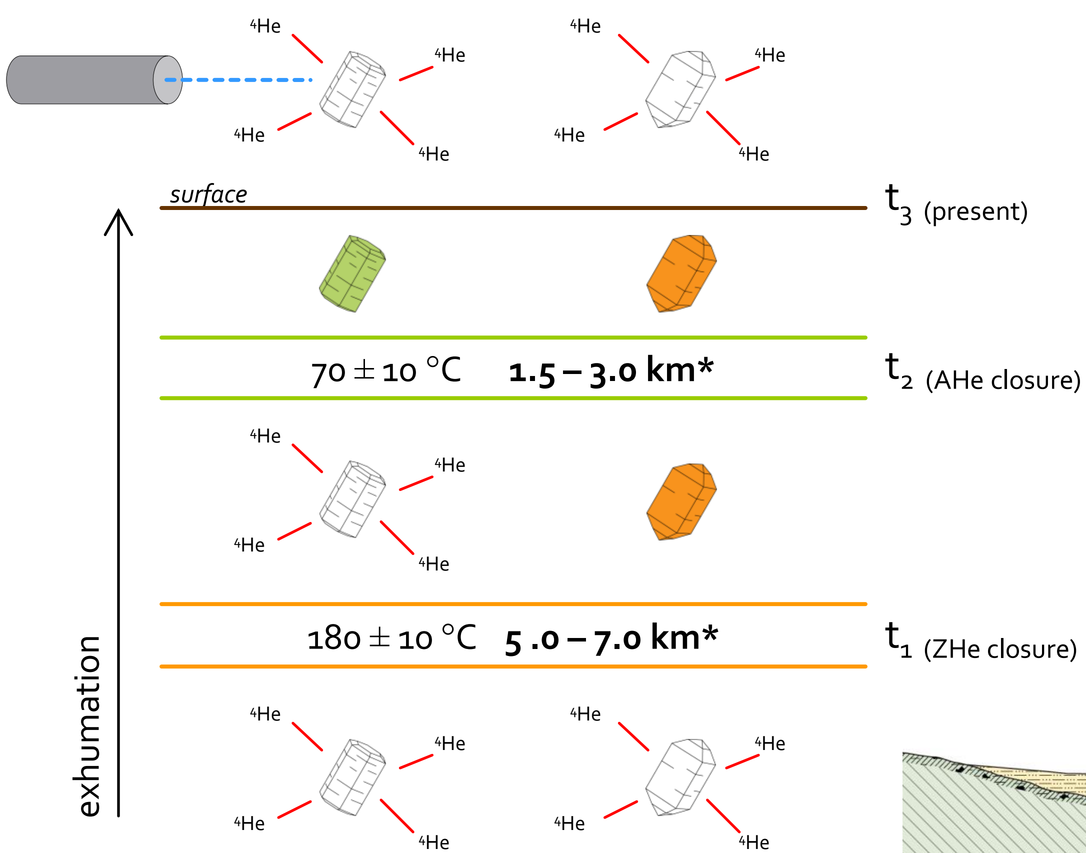
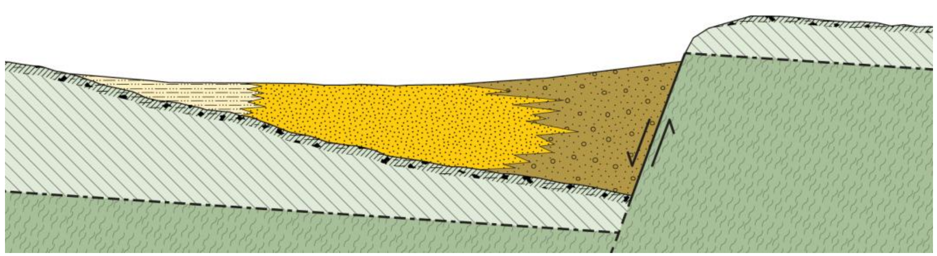


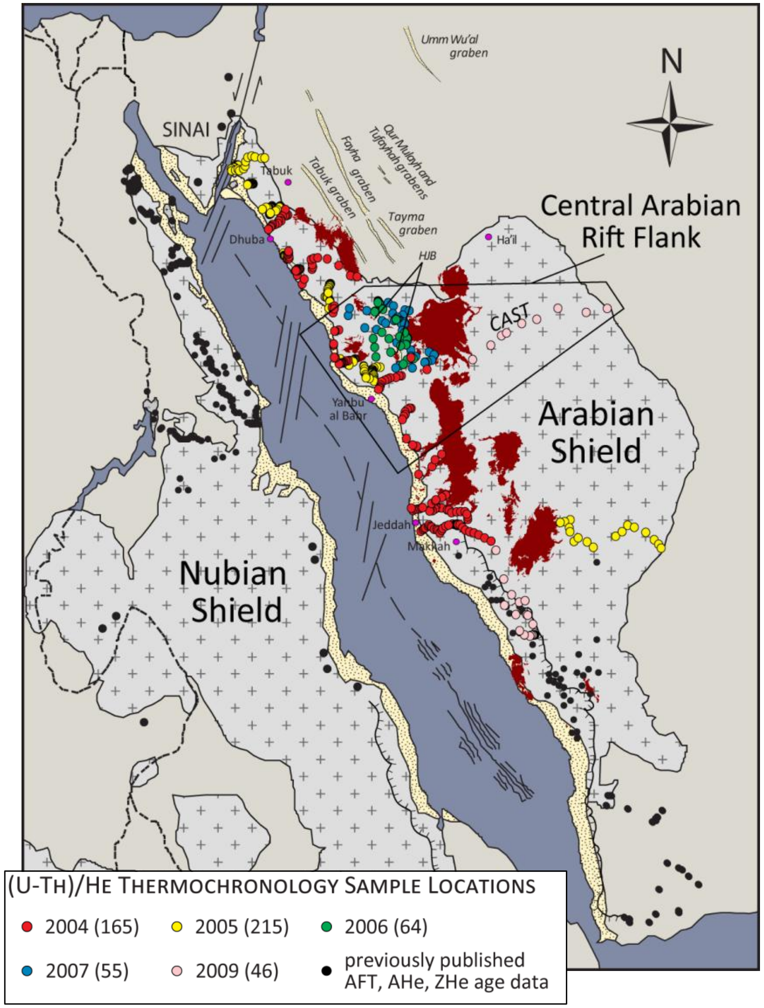
AHe
- footwall exhumation (time and rate)
- sedimentary strata deposition timing
- pre-rift burial magnitude

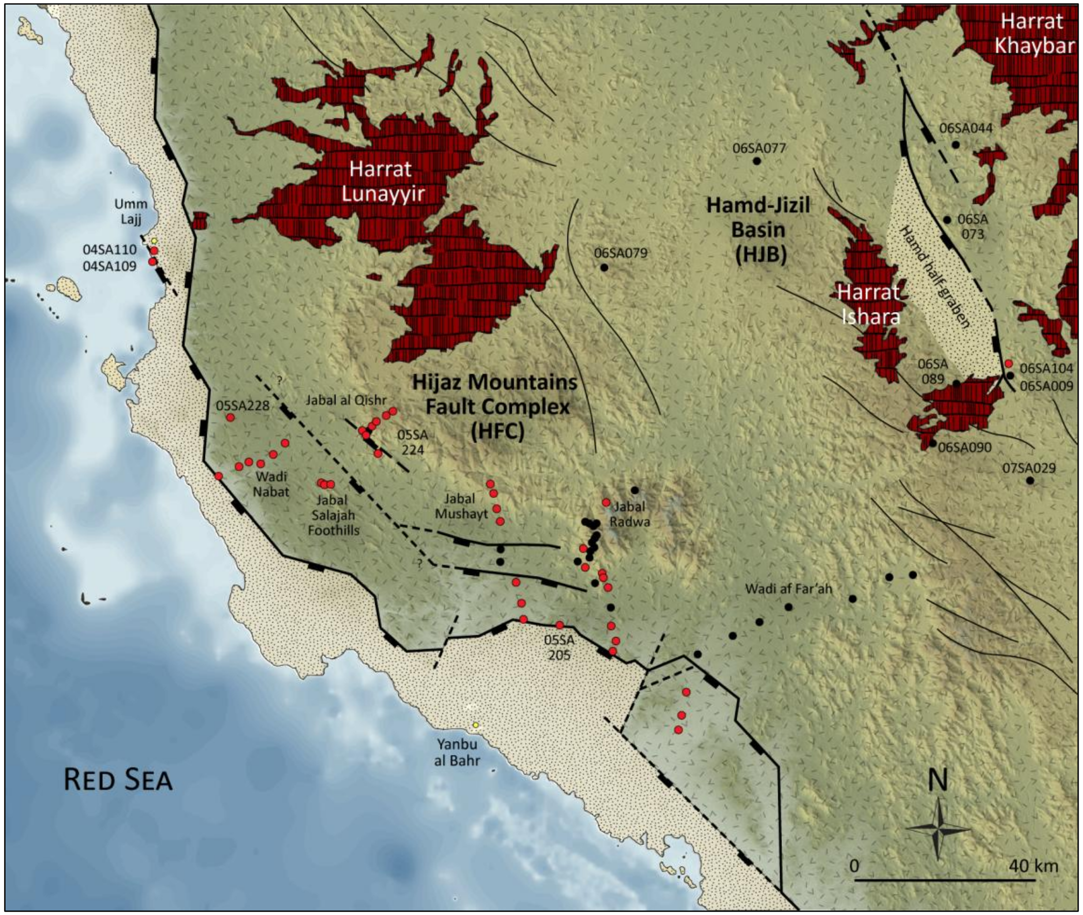
ZHe
- t-T history via numerical modeling



Assuming average 25 °C/km geothermal gradient and average surface T = 25 °C.

2 Central Arabian Rift Flank structural domains: Hijaz Mountains Fault Complex (HFC) & Hamd-Jizil Basin (HJB)





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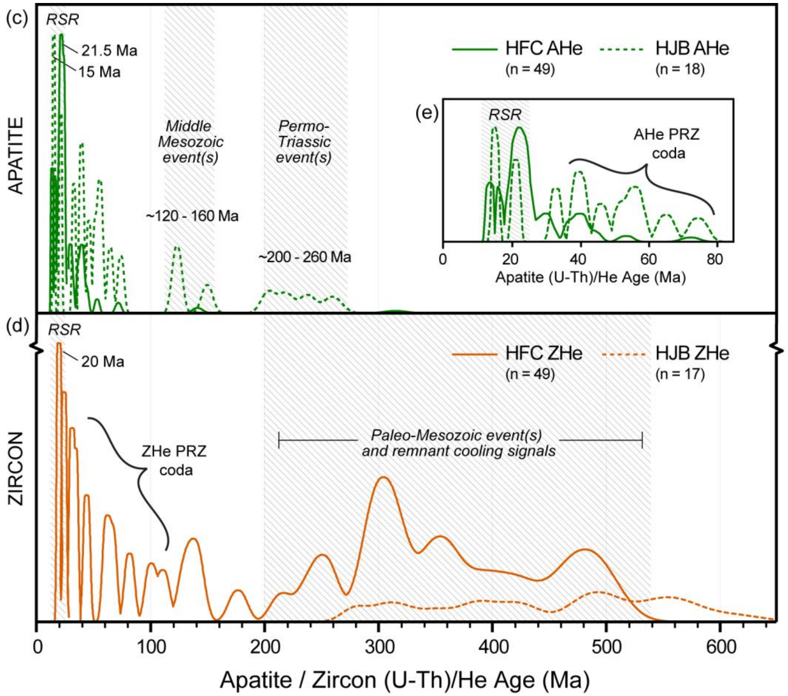
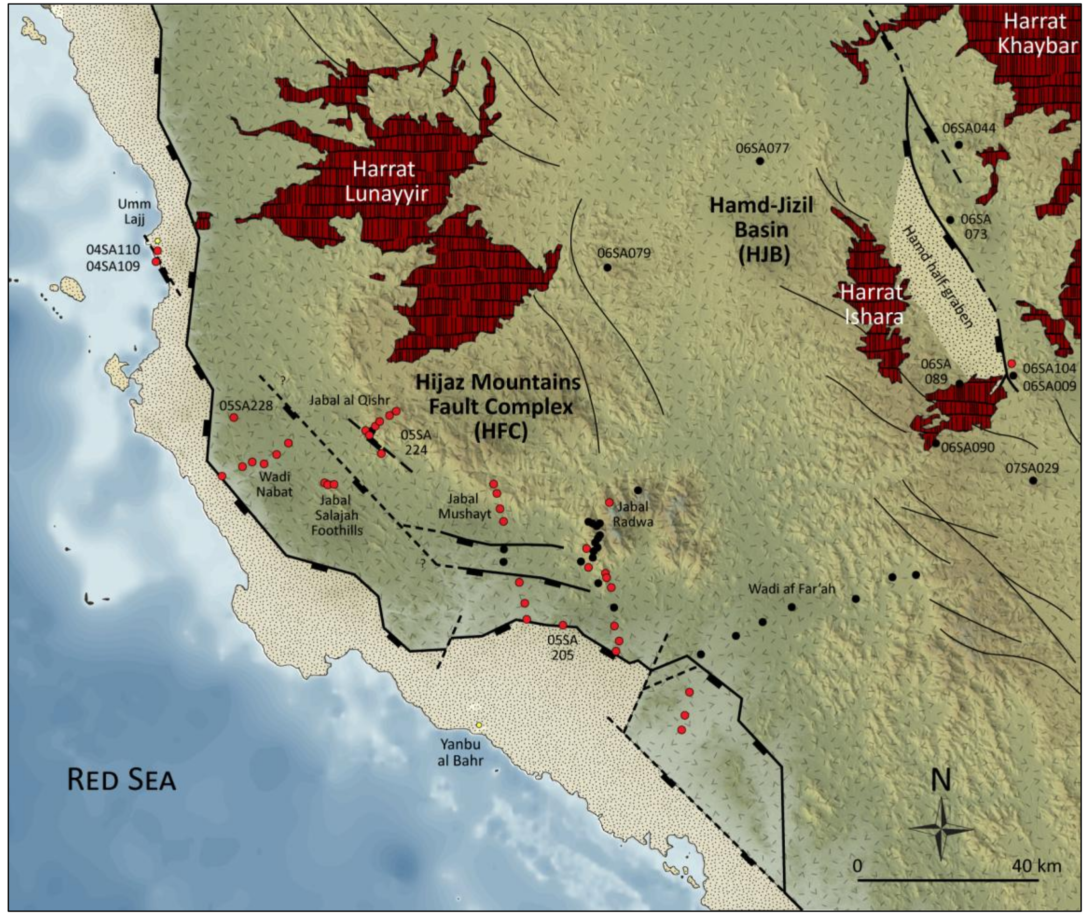
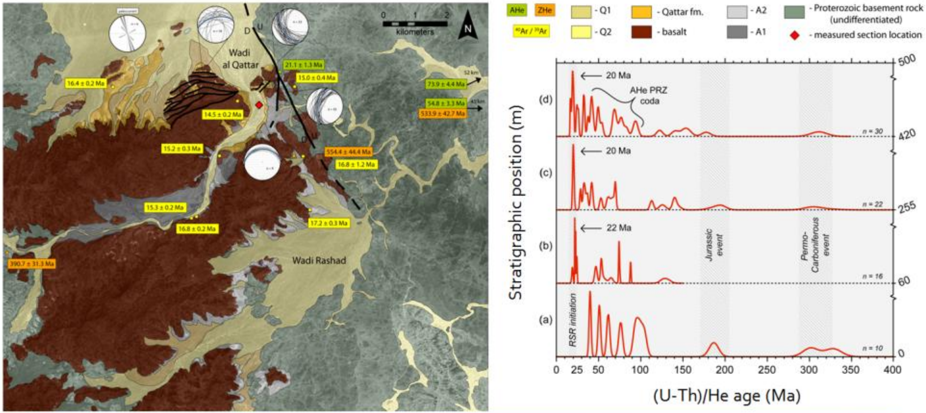
Hijaz Mountains Fault Complex (HFC) & Hamd-Jizil Basin (HJB)





- raw AHe, ZHe data show RSR footwall exhumation in both domains ~21 Ma
- dissimilarity in AHe, ZHe age spectra between two domains: indicator of different rift history
- HJB retains older ZHe ages; HFC yields the greater RSR-related exhumation record

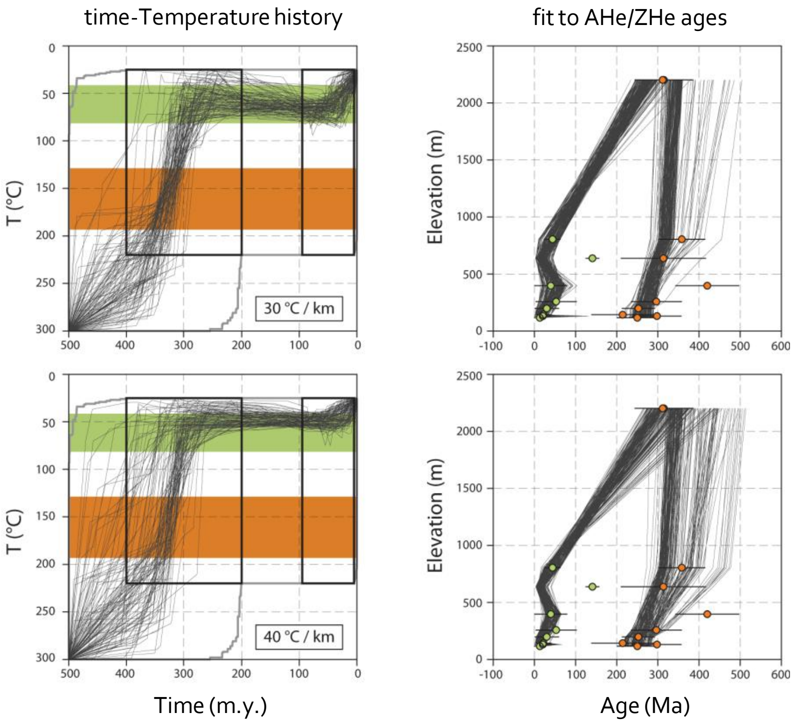
Bedrock AHe, ZHe and detrital AHe ages – Hamd-Jizil Basin

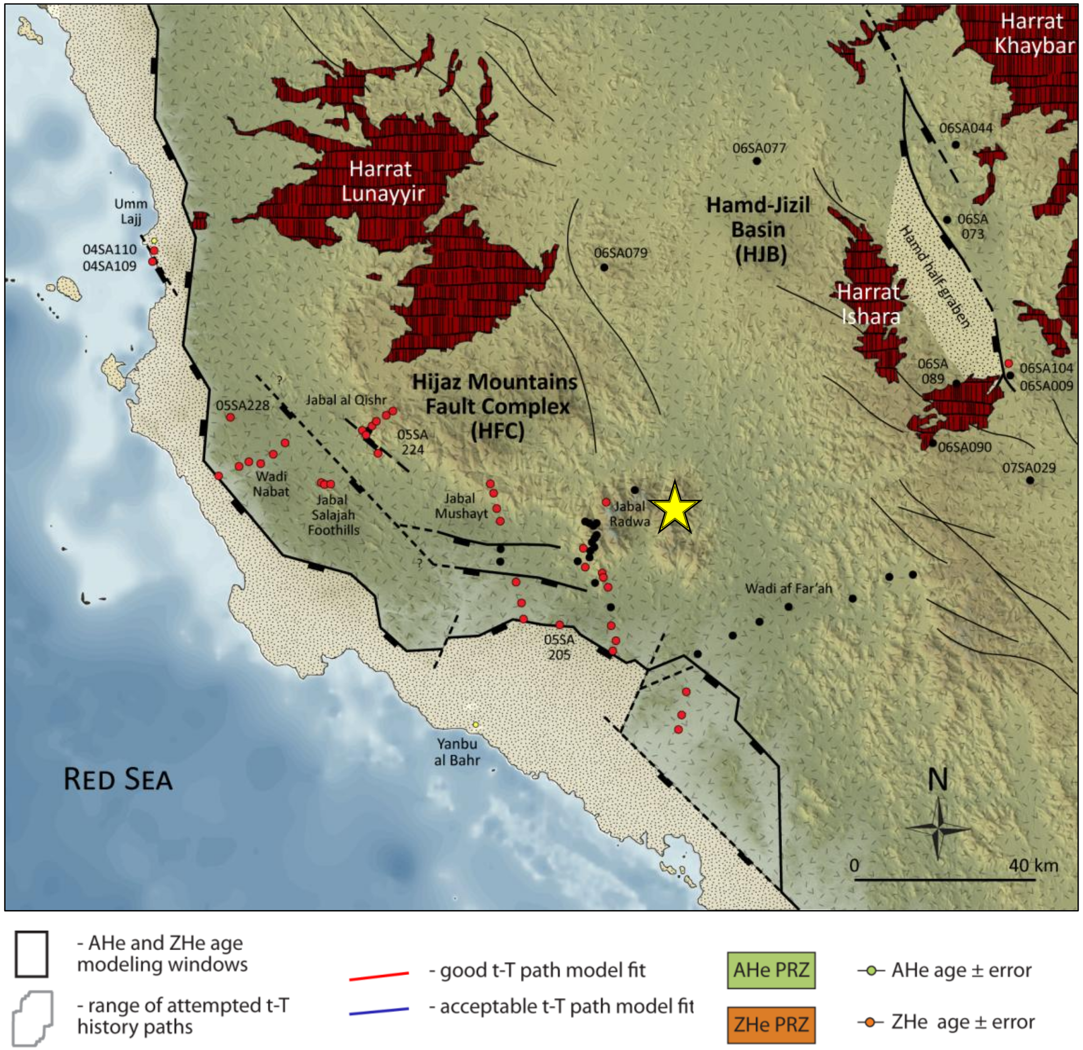


Presenter's notes: A He age spectra evolution shows unroofing of proximal footwall. Jurassic and older ages identify older cooling events in Shield.

t-T model of paleo-geothermal gradient – Hijaz Mountains Fault Complex

*see Hager et al., 2012 AAPG ACE abstract #1240994





No signal indicating significant accumulation of pre-rift volcanic or sedimentary overburden

Absence of signal to indicate increased heat flow in mid- to upper-crustal levels during RSR initiation

t-T model of paleo-geothermal gradient – Hijaz Mountains Fault Complex

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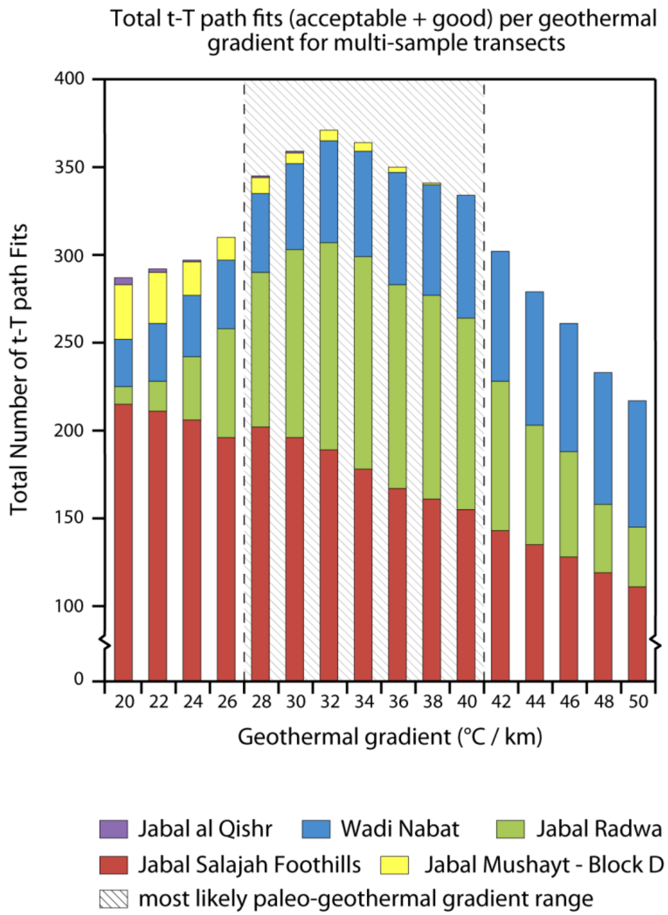

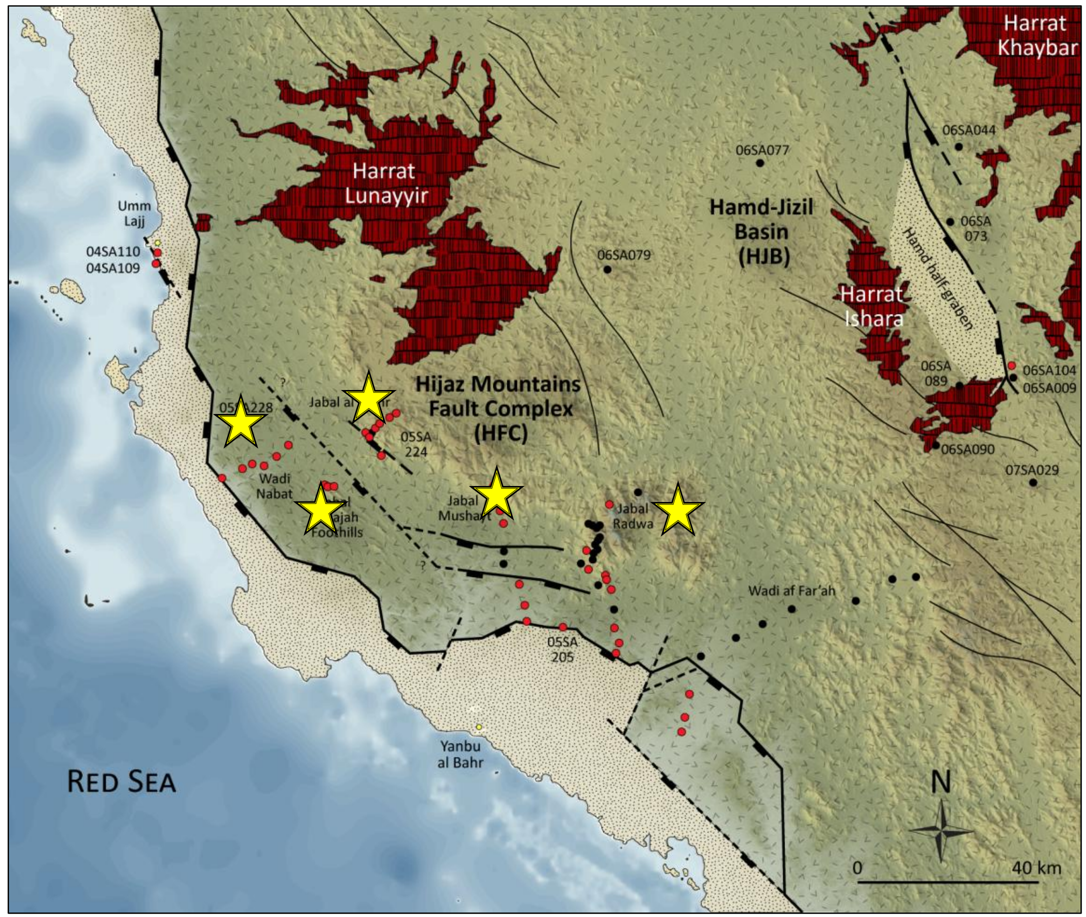

Other multi-sample transects less constrained yet fit Jabal Radwa model

Paleo-geothermal gradient range: 28 – 40 °C/km

Bedrock and t-T modeled AHe, ZHe ages – Hijaz Mountains Fault Complex

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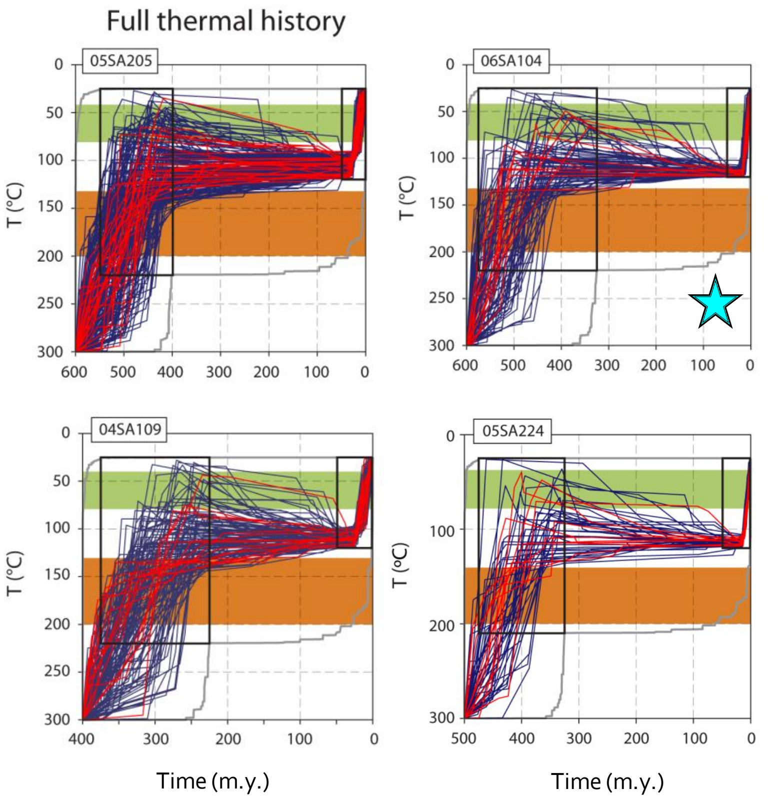

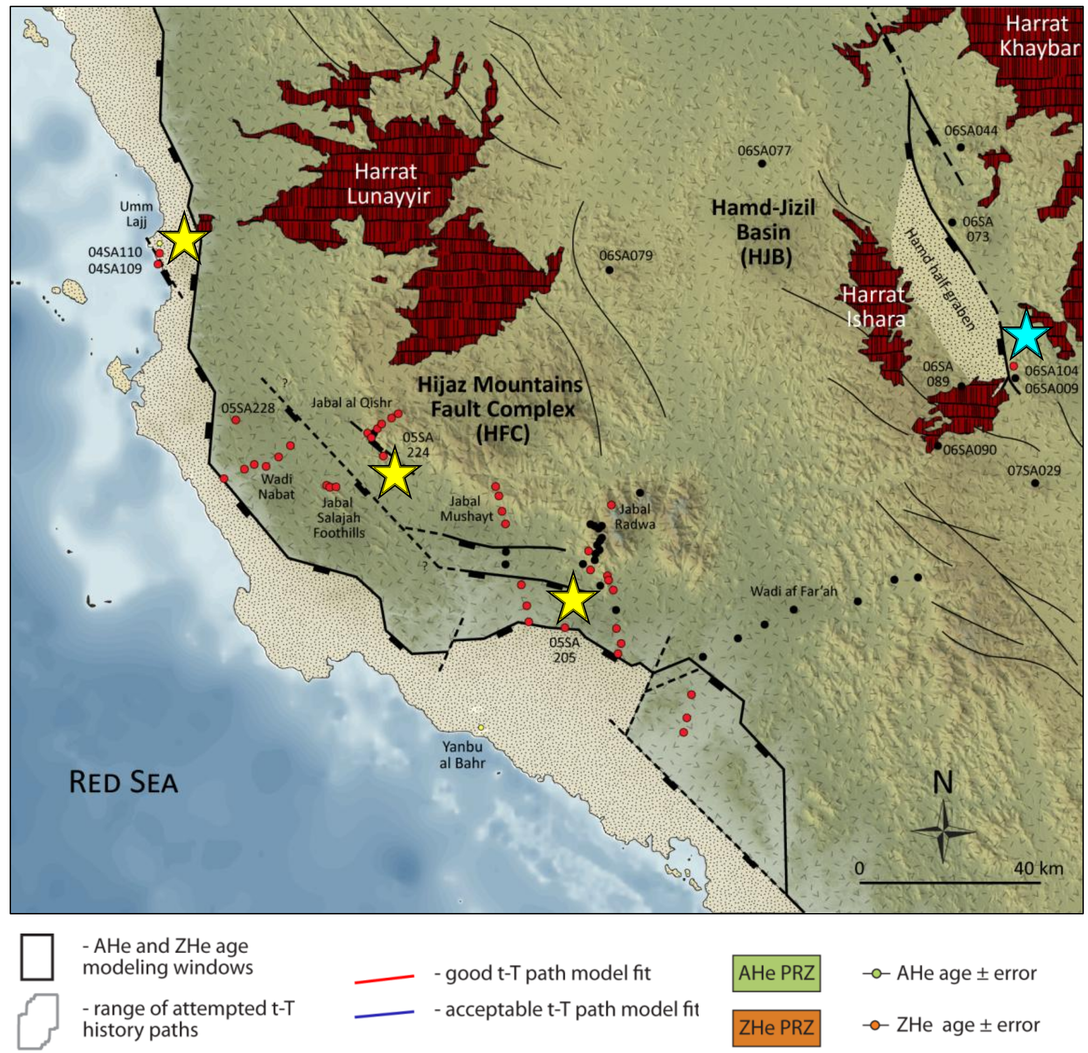

Paleo-Mesozoic: CARF cooled through ZHe PRZ minimal reheating paths; RSR initiation: ~21 Ma; further exhumation in HJB and HFC: ~15 Ma

Exhumation ~2.0 – 3.3 km

Bedrock and t-T modeled AHe, ZHe ages – Hijaz Mountains Fault Complex

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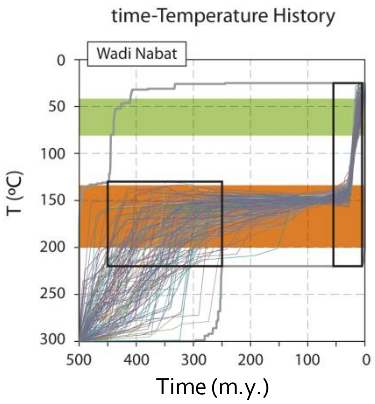
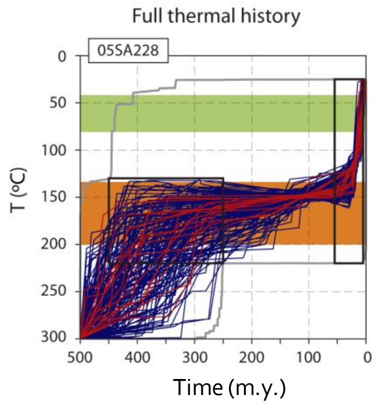
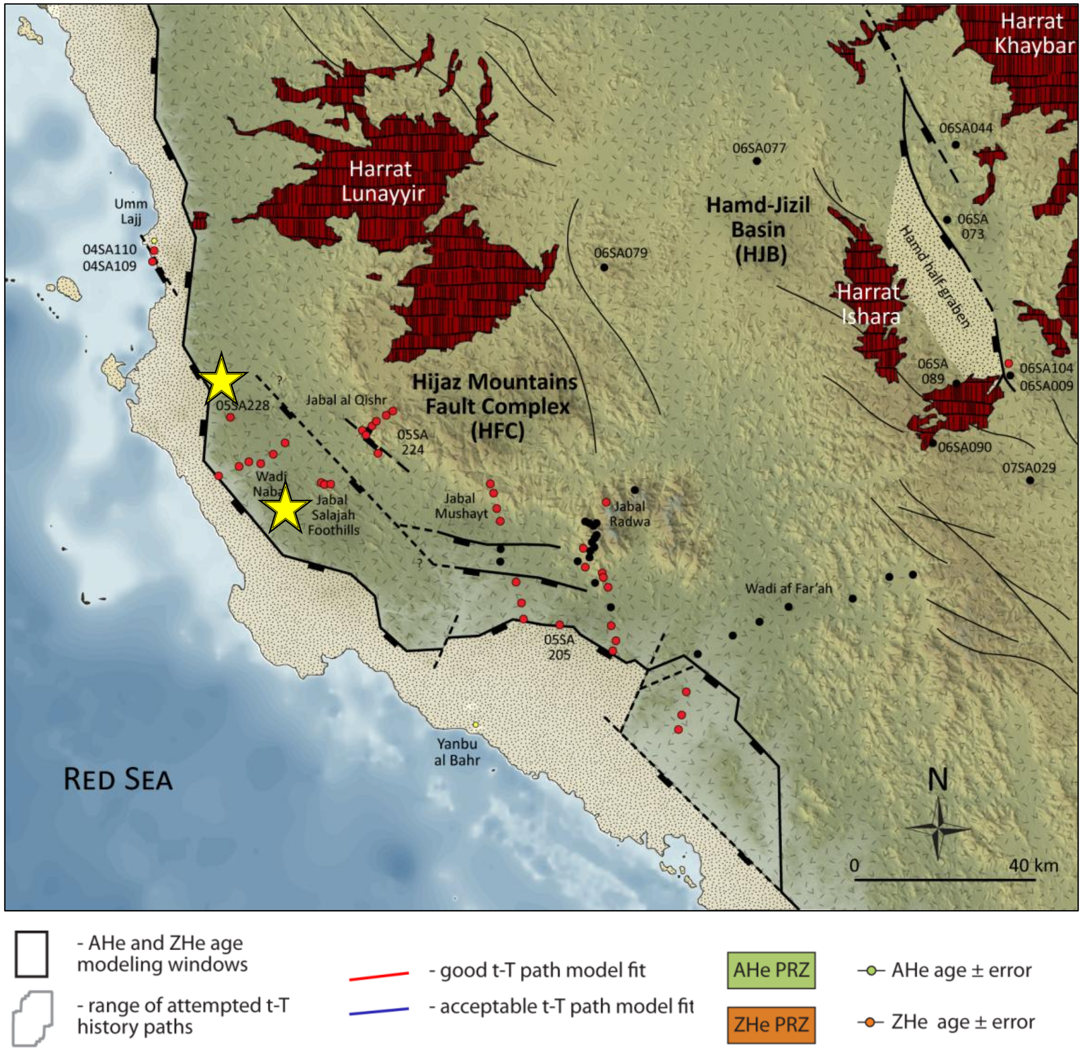




Paleo-Mesozoic: CARF cooled into ZHe PRZ; again, minimal reheating paths

Footwall exhumation ~3.9 km



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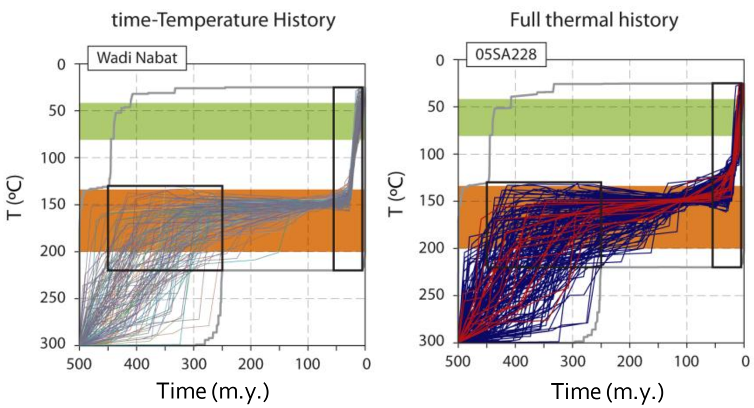
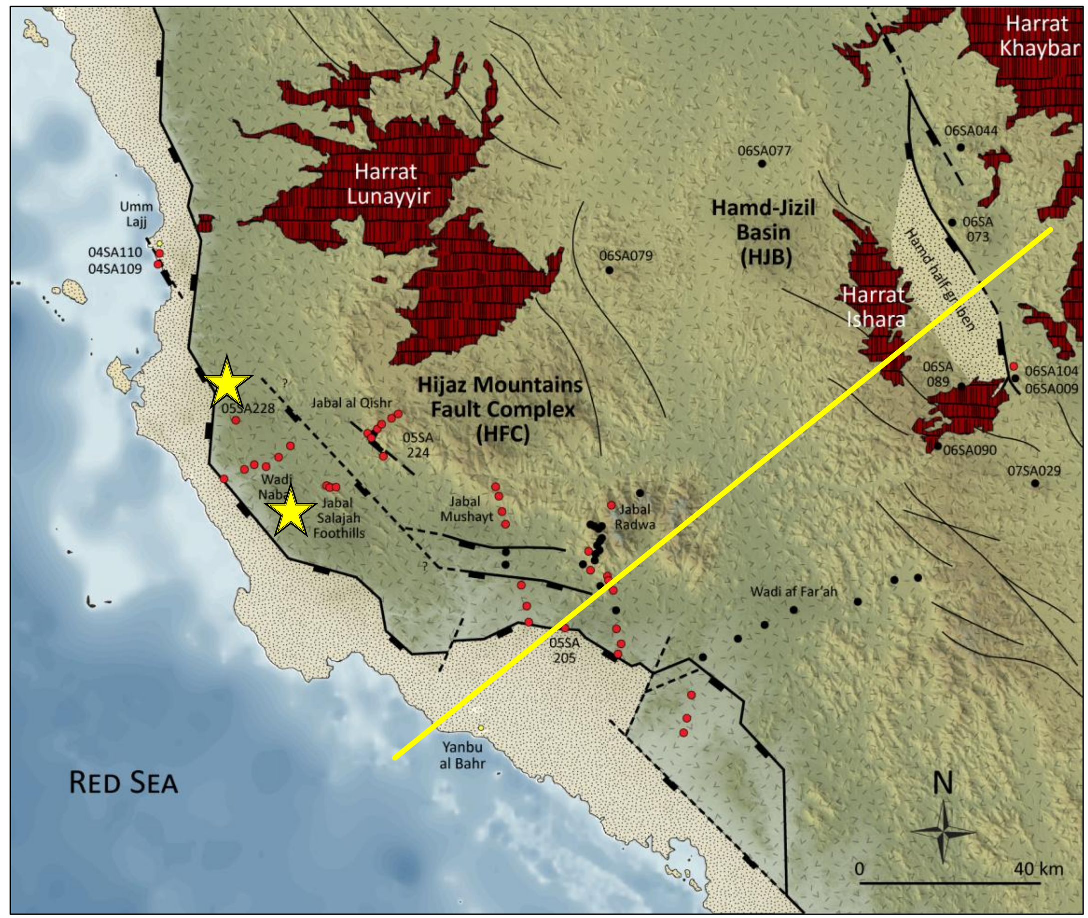


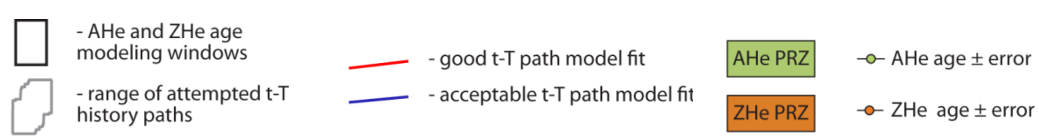
CARF: 3-stage thermotectonic t-T history

1. Paleo-Mesozoic cooling to mid- to upper-crustal structural levels
2. Relative thermal stability until Miocene
3. RSR footwall exhumation: 23 Ma

Diffuse rift-related deformation; sustained for ~8 million years

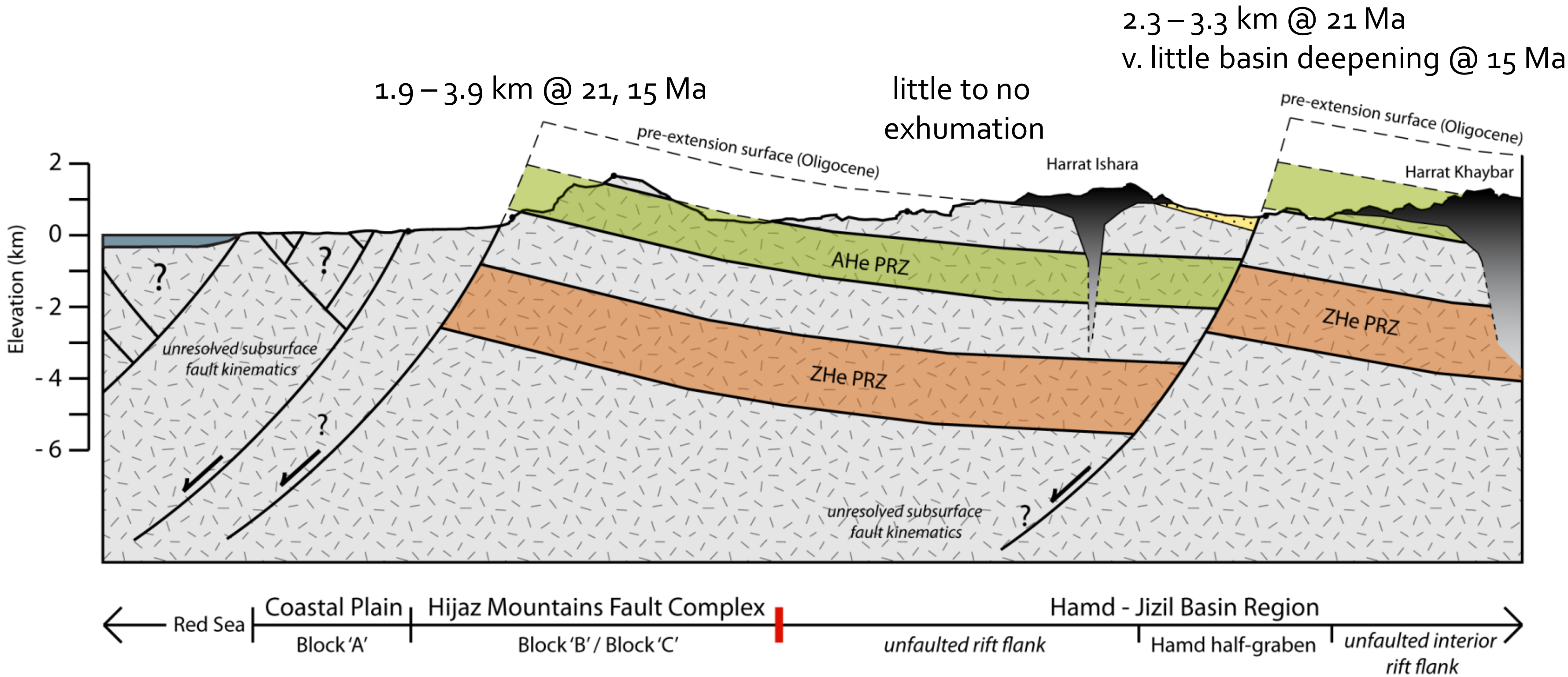
Footwall exhumation from pre-rift flank depths of ~1.5 – 3.9 km; variability across the CARF





Crustal cross-section – Central Arabian Rift Flank

- 200km –wide zone of diffuse extension
- harrat volcanism trailed rift onset by ~6 million years



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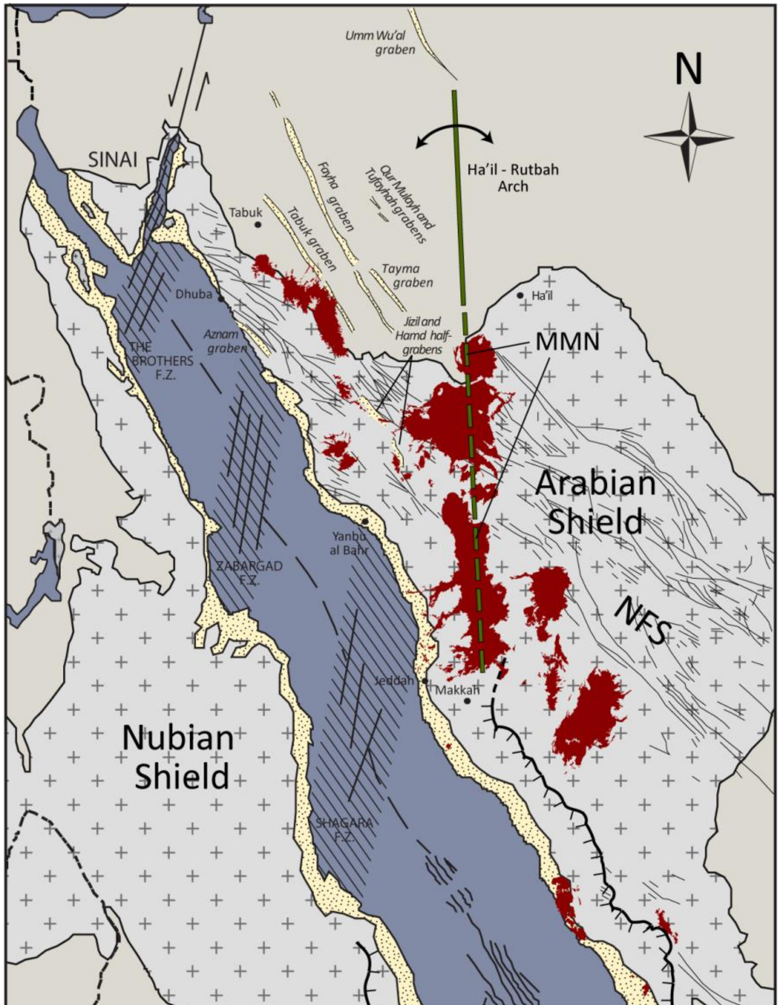


MAJOR GEOLOGIC FEATURES OF THE CENTRAL AND NORTHERN RSR

- Arabian - Nubian Shield
- Paleo-Mesozoic Sedimentary and Volcanic Cover
- Coastal (Great) Escarpment
- Najd Fault System (NFS)
- Cenozoic Sedimentary Deposits
- Cenozoic basalt
- Cenozoic grabens
- RSR axial trace
- RSR transfer zones
- Oceanic Crust

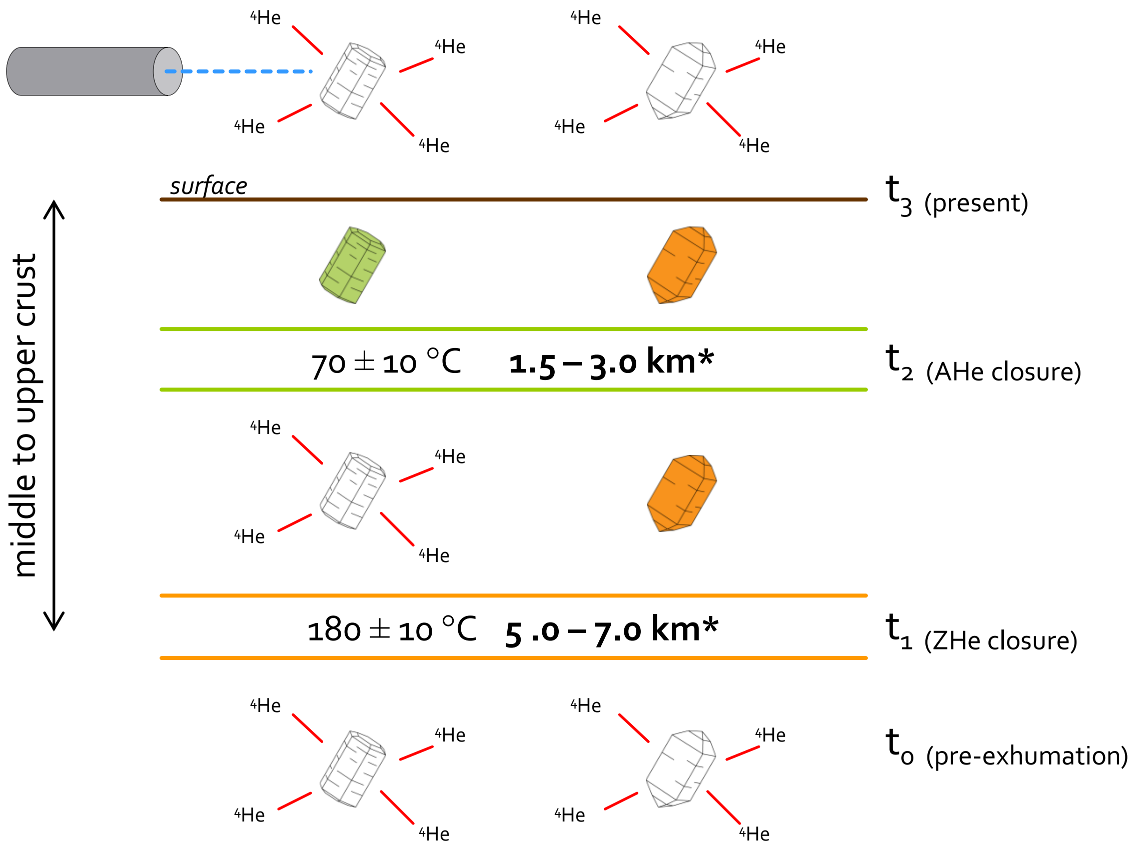
SUMMARY

- No significant pre-rift flank burial at CARF latitude
- No significant indication of increased geothermal gradient prior to rift initiation (i.e., passive rifting in CARF)
- Concomitant along-strike rift initiation ~23 Ma
- Dissimilar structural architecture on either side of 21 °N:
  - CARF fault blocks exhumed along numerous rift-parallel footwalls from pre-rift flank depths of ~1.5 – 3.9 km across a 200 km-wide zone of diffuse extension
  - Diffuse extension for ~8 million years
  - Strain migration ~15 Ma from CARF/NARF to RSR axial trough with advent of Dead Sea transform
  - Cenozoic graben to NNW likely share similar history with HJB

- NARF pre-rift history still TBD
- Examine basin core and explore HJB evacuation timing? Link to CARF/NARF exhumation?

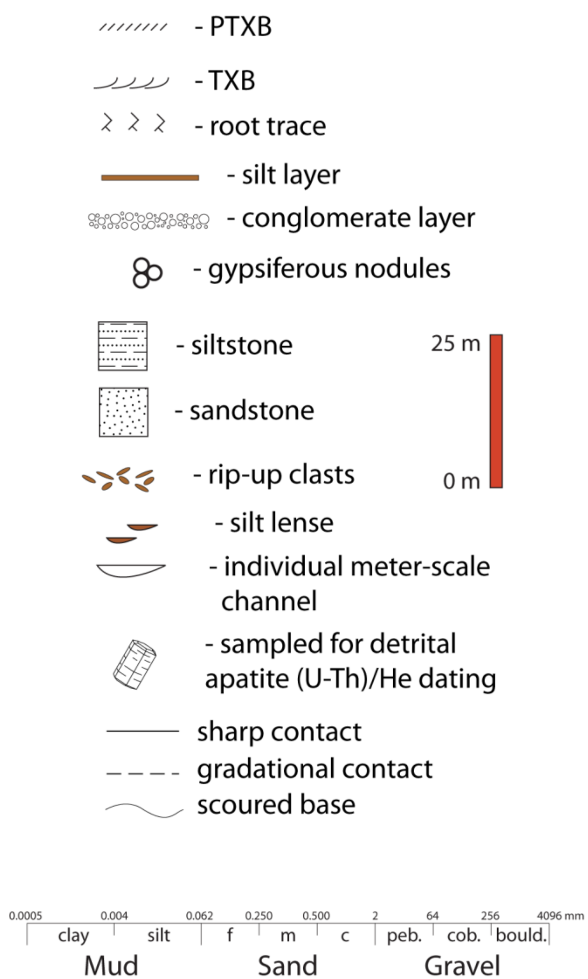
BACKUP

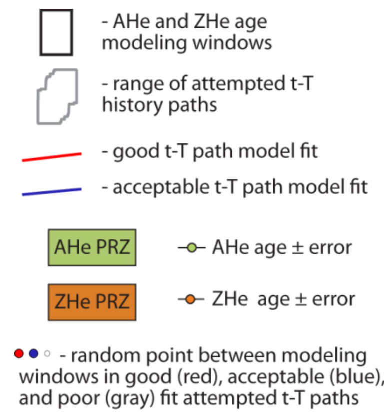
Low-T thermochronology Primer



**Assuming average 25 °C/km geothermal gradient and average surface T = 25 °C.*

LEGENDS


- PTXB
- TXB
- root trace
- silt layer
- conglomerate layer
- gypsiferous nodules
- siltstone
- sandstone
25 m
0 m
- rip-up clasts
- silt lense
- individual meter-scale channel
- sampled for detrital apatite (U-Th)/He dating
sharp contact
gradational contact
scoured base
0.0005 0.004 0.062 0.250 0.500 2 64 256 4096 mm
clay silt f m c peb. cob. bould.
Mud Sand Gravel


- AHe and ZHe age modeling windows
- range of attempted t-T history paths
- good t-T path model fit
- acceptable t-T path model fit
AHe PRZ
AHe age ± error
ZHe PRZ
ZHe age ± error
- random point between modeling windows in good (red), acceptable (blue), and poor (gray) fit attempted t-T paths

Hamd-Jizil Basin