**Active Lithospheric Thinning at the Red Sea Margin Implicated by Sub-Moho Earthquakes**

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**Motivation**

- Adjacent to Red Sea: Moho at 38 ± 2 km, LAB at 60 ± 5 km
- LAB ~160 km under Arabian Platform
- High-frequency earthquakes at 40–50 km imply brittle failure
- Brittle failure requires $T < 600–800°C$
- Geothem is in disequilibrium → recent lithospheric thinning

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**The Arabian Plate**

- Harrat Lunayyir: Shallow dike intrusion in 2009
- Harrat volcanism < 10 Ma (Lunayyir since 1 Ma)
- Harrat Lunayyir: Shallow dike intrusion in 2009

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**CCP Analysis and Sub-Moho Earthquakes**

3a) Harrat Lunayyir CCP
- Moho at depth of ~38 km
- LAB at 60 km, much less than twice the Moho depth, cannot be produced by simple PPs or PPs multiples
- Hansen et al. (2007) used P to P receiver functions to estimate the LAB at ~55 km to the west of Harrat Lunayyir
- Chang et al. (2011) estimated LAB depth using tomography as ~70 km

3b) Sub-Moho Earthquake Locations
- Most catalog-reported 72 events below the Moho during 2014
- P and S arrivals picked manually
- Events relocated using Hypoinverse followed by double-difference relocation using HYPODD with u=0.1
- Isolated & longitudinal extent of map corresponds to extent of 4a
- Orange circles are the locations of the sub-Moho earthquakes
- Earthquakes are at the edge of the array, perhaps at a new plate boundary
- Dark gray are the volcanics
- Dashed line is 2009 dike intrusion

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**Data and Processing**

- CCP Image (3a)
  - Average station spacing of 10 km
  - P to S receiver functions calculated for 857 events
- RFs cross correlated with a station stack to remove noise signals
- Conventional Continuation Point (CCP) stacks calculated on a 2 x 2 x 2 km grid (3a)

- 3b) Typical High Frequency Earthquake
  - Earthquake recorded at station LNS02
  - High-pass filtered 3 Hz
  - P and S both have impulsive arrivals

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**Locations and Temperature Constraints**

4a) Final Event Locations
- Gray circles: catalog locations
- Blue relocated
- After relocation, 68 events M ≥ 3 between Moho and LAB
- Events clustered in depth range 40–50 km

4b) Temperature Range of Brittle Failure
- Curves show the boundary between velocity-weakening (brittle failure possible) and velocity-strengthening (plastic failure) for different values of DMM. The value of $DMM$ is a function of temperature, stress, and strain rate.
- Both sets of experiments imply brittle behavior below 600°C, and perhaps below 500°C.

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**Thermal Modelling**

5a) Model
- At time $t = 0$ Ma, Moho is thinned from 150 km to 90 km
- LAB depth at paper held at 1400°C (plume material?)
- Surface held at 0°C

5b) Thermal Evolution:
- Evolution of geotherm in time
- Line at 50 km marks approximate depth limit of sub-Moho earthquakes
- Tang et al. (2016) assumed for mantle 3rd temperatures of 1400°C at 90 km beneath Harrat Lunayyir
- Region of earthquakes reaches ~800°C at ~1 Myr and 900°C at ~3 Myr

5c) Temperature at 50 km:
- Tang et al. (2015) showed 800°C at 50 km is the approximate temperature for hot plume material (1500°C) only 1.5 Ma
- Lherzolite has been denn for within the last 3 Ma
- Is 800°C the appropriate temperature cut-off for earthquakes due to lifting?

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**Conclusions**

- If high-frequency sub-Moho earthquakes imply brittle failure, then the temperature must be < 600–800°C
- Hence lithosphere must have thinned within the last 3 Ma

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**References**

- King and Marone (2012)
- Tang et al. (2016)
- Hansen et al. (2007) used S to P receiver functions to estimate the LAB at depth of ~38 km
- Most catalog-reported 72 events below the Moho during 2014
- Dashed line is 2009 dike intrusion
- Original LAB 150 km
- LAB depth at paper held at 1400°C (plume material?)
- Surface held at 0°C