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

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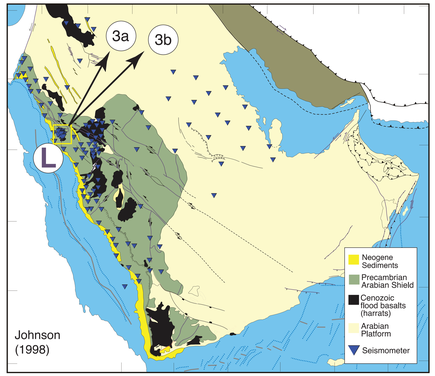
Motivation

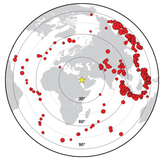
- Adjacent to Red Sea: Moho at 38 ± 2 km; LAB at 60 ± 5 km
- LAB ~160 km under Arabian Platform
- High-frequency earthquakes at 40–50 km imply brittle failure
- Brittle failure requires T < 600–800°C
- Geotherm is in disequilibrium → recent lithospheric thinning

1 The Arabian Plate



- Harrat Lunayyir: Shallow dike intrusion in 2009
- Harrat volcanism < 10 Ma (Lunayyir since 1 Ma)
- Red Sea: seafloor spreading in south since 5 Ma; rifting since 25 Ma

2 Data and Processing



Event distribution. Star at Mecca, Saudi Arabia. Red circles are earthquakes scaled to magnitude.

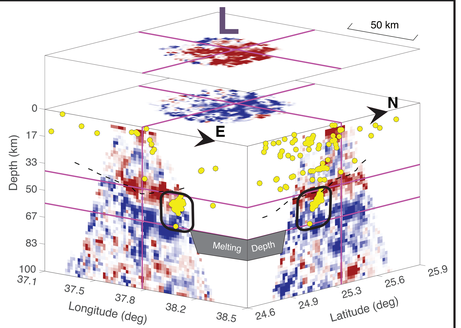
CCP Image (3a)

- 18 stations in Harrat Lunayyir from 2008 to early 2015
- Average station spacing of 10 km
- P to S receiver functions calculated for 857 events
- RFs cross correlated with a station stack to remove noisy signals
- Common Conversion Point (CCP) stacks were calculated on a 2 x 2 x 2 km grid (3a)

3 CCP Analysis and Sub-Moho Earthquakes

3a) Harrat Lunayyir CCP

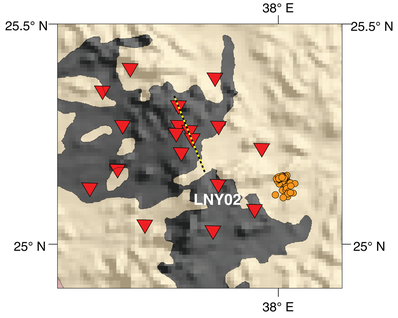
- Moho at depth of ~38 km
- LAB at 60 km, much less than twice the Moho depth; cannot be produced by simple PsPs or PsSs multiples
- Hansen et al. (2007) used S to P receiver functions to estimate the LAB at ~55 km to the west of Harrat Lunayyir
- Chang et al. (2011) estimated LAB depth using tomography as ~70 km
- Camp and Roobol (1992) estimate the melting depth as 60–70 km, below the LAB



3D CCP cube for Harrat Lunayyir. Cube faces: magenta lines. Horizontal lines: constant depth slices, vertical lines: N–S and W–E slices. Reds are positive amplitudes (velocity increases down, e.g. Moho) and blues are negative amplitudes (e.g. LAB). Yellow circles on 4a are catalog earthquake locations with depths ≥ 30 km or magnitudes ≥ 2.

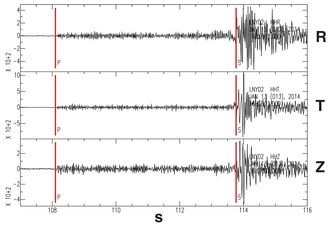
3b) Sub-Moho Earthquake Locations

- SGS 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 iasp91
- Latitudinal & longitudinal extent of map corresponds to extents of 4a
- Orange circles are the locations of the sub-Moho earthquakes
- Earthquakes are at the edge of the array, relocation is a big improvement
- Dark gray are the volcanics (< 1 Ma in Lunayyir)
- Dashed line is 2009 dike intrusion



3c) Typical High Frequency Earthquake

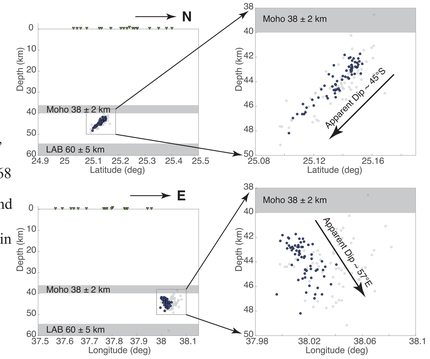
- Earthquake recorded at station LNY02
- High-pass filtered: 1 Hz
- P and S both have impulsive arrivals



4 Locations and Temperature Constraints

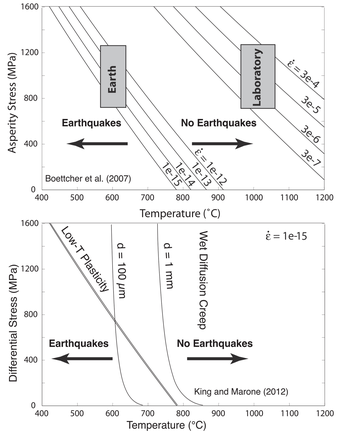
4a) Final Event Locations

- 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

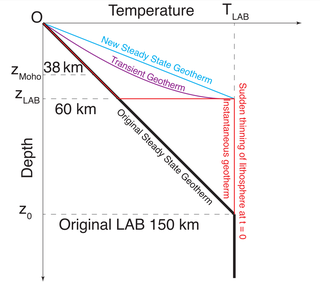
- Curves show the boundary between velocity-weakening (earthquakes possible) and velocity-strengthening (no earthquakes) for different values of strain rate as a function of temperature
- Both sets of experiments imply brittle behavior below 600°C, and perhaps below 800°C



5 Thermal Modelling

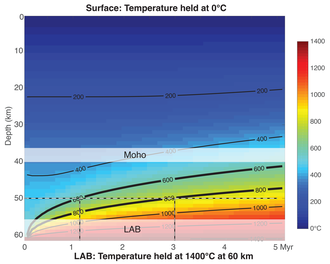
5a) Model:

- At time t = 0 Ma lithosphere is thinned from 150 km to 60 km
- Temperature at LAB held at 1400°C (plume material?)
- Surface held at 0°C



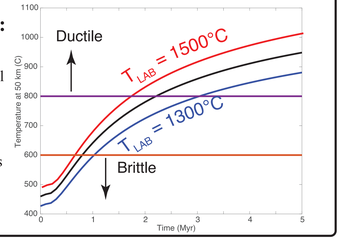
5b) Thermal Evolution:

- Evolution of geotherm in time
- Line at 50 km marks approximate depth limit of sub-Moho earthquakes
- Tang et al. (2016) inverted V_s for mantle lid temperatures of 500–800°C at 40–60 km beneath Harrat Lunayyir
- Region of earthquakes reaches 600°C at ~1 Myr and 800°C at ~3 Myr



5c) Temperature at 50 km:

- Time to reach 800°C at 50 km depth depends on asthenospheric temperature; for hot plume material (1500°C) only 1.5 Ma
- Lithosphere has been thinned within the last 3 Ma
- Is 800°C the appropriate temperature cut-off for earthquakes due to diking?



6 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

(Future work: Refine geothermal model)

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