Aftershock Activity at Intermediate-Depth Earthquakes in Northern Chile Controlled by Plate Hydration

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Intermediate Depth Earthquakes (IDEs)

- Their rupture mechanism is still poorly understood (Frohlich, 1987; Houston, 2015).
- A general lower aftershock productivity has been observed as compared with shallower events (Frohlich, 1987; Wiens et al., 1994; Zhan, 2014; Houston, 2015)

Northern Chile

- We investigate the variations of the seismic source properties and aftershock activity using kinematic inversions (KI) and template-matching (TM), for the six (E1 to E6) largest magnitude (Mw ~6.3) intermediate-depth earthquakes occurred in northern Chile since 2010.

Fig. 1:
Northern Chile Events:

• Registered by a dense network of broad-band and strong-motion sensors in the near-field, due to they are located where the Centro Sismológico Nacional (CSN; Barrientos et al., 2018), Integrated Plate Boundary Observatory Chile (IPOC; GFZ, & CNRS-INSU, 2006) and Central Andean Uplift and the Geodynamics of the High Topography (CAUGHT; Beck et al., 2010) seismic networks have been deployed.

• Broad-Band  → Template Matching (TM)
• Strong-Motion  → Kinematic Inversions (KI)

• Located at different distances from the top of the slab:
  (Mainshock and aftershock hypocenters reported by CSN are plotted)

Fig. 1:
Detection of aftershocks using template matching:

- We searched for events with similar waveforms to those reported as mainshock and aftershocks for the CSN, considering the five nearest stations to the source region of each event.
- For E2, E5 and E6 no aftershocks were reported by CSN, USGS, etc.

Fig. 2:
Kinematic Inversions using Strong-Motion data:

• We assume a finite-fault model with an a-priori elliptical-patch slip distribution (Ruiz et al., 2019 and references therein).

• **We inverted seven parameters.** Five of them correspond to geometrical characteristic: semi-axes $a$ and $b$ of the ellipse, the rotation angle of the ellipse $\alpha$ and the location $(x_0, y_0)$ of its center into the fault plane, and the other two parameters are maximum slip $D_{\text{max}}$ and rupture velocity $V_r$. 

Fig. 3: Observed Simulated
Thermal Model using Finite Element Method (FEM):

In order to assess the thermal conditions at the depth of the analyzed events, we developed a **2D-thermal model using Finite Element Method (FEM)** for northern Chile, along the BB’ profile (Fig.1). The model is constrained by the plate geometry of SLAB2.0 (Hayes et al., 2018), hypocenter data, and published thermal parameters in the area.

Fig. 4:
Results

- All events have tensional focal mechanism and span a range of depth from 90 to 130 km (Fig, 1), in a region where a double seismic zone (DSZ) has been previously reported (Comte et al., 1999; Dorbath et al., 2008; Sippl et al., 2018; Florez & Prieto, 2019).

- The number of aftershocks show a clear reduction as function of depth, down to E6 that is showing no aftershocks (Figures 5a-c).

- It is important to highlight that there are no aftershocks reported in the CSN catalog for E2, E5, and E6. For these events, we use the mainshock waveforms for detection. This strategy permits to find new events for E2 and E5.
Results

- E1 and its aftershocks occurs near the 400 °C isotherm-depth and does not exceed the 450 °C isotherm, while the rest of the events occurs below this isotherm.

- Our analysis clearly reveals an inverse relationship between the number of aftershocks and temperature.

Fig. 5: Results
Results

- Our results show similar geometries of rupture (Table 1), with an approximately circular rupture ranging from ~3.5 to ~5 km.

- The estimated stress drop values vary between 7.5 MPa and 29.5 Mpa.

- Despite a variability of rupture parameters exists (Table 1), we do not see any clear correlation between them and the depth of the events. We thus suggest that the analyzed events, while occurring under different thermal conditions, all have a similar rupture physics.

<table>
<thead>
<tr>
<th>Event</th>
<th>$a$ (km)</th>
<th>$b$ (km)</th>
<th>$D_{\text{max}}$ (m)</th>
<th>$V_r$ (km/s)</th>
<th>Stress drop (MPa)</th>
<th>Number of aftershocks</th>
<th>Distance from the top of the slab (km)</th>
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</thead>
<tbody>
<tr>
<td>E1</td>
<td>3.49</td>
<td>5.13</td>
<td>1.08</td>
<td>1.07</td>
<td>18.2</td>
<td>2044</td>
<td>7</td>
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<tr>
<td></td>
<td>3.67</td>
<td>5.68</td>
<td>0.94</td>
<td>1.19</td>
<td>14.7</td>
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<td>E2</td>
<td>4.38</td>
<td>6.99</td>
<td>0.65</td>
<td>1.59</td>
<td>8.5</td>
<td>123</td>
<td>12</td>
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<tr>
<td></td>
<td>4.12</td>
<td>6.58</td>
<td>0.73</td>
<td>1.51</td>
<td>9.9</td>
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<td>E3</td>
<td>5.05</td>
<td>6.16</td>
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<td>0.67</td>
<td>14.3</td>
<td>30</td>
<td>14</td>
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<td></td>
<td>4.14</td>
<td>6.44</td>
<td>1.24</td>
<td>0.82</td>
<td>16.7</td>
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<td>E4</td>
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<td>0.73</td>
<td>1.22</td>
<td>12.8</td>
<td>46</td>
<td>20</td>
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<tr>
<td></td>
<td>4.56</td>
<td>5.60</td>
<td>0.52</td>
<td>1.91</td>
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<td>E5</td>
<td>5.89</td>
<td>4.25</td>
<td>0.71</td>
<td>1.68</td>
<td>10.0</td>
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<td>0.60</td>
<td>2.20</td>
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<td>E6</td>
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<td>1.61</td>
<td>0.68</td>
<td>29.5</td>
<td>0</td>
<td>41</td>
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<tr>
<td></td>
<td>3.43</td>
<td>6.40</td>
<td>0.95</td>
<td>0.80</td>
<td>14.1</td>
<td></td>
<td></td>
</tr>
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</table>

Table 1: Resume of kinematic parameters and number of aftershocks obtained for each mainshock.

Note: Green and yellow rows indicate parameters obtained using nodal plane 1 (NP1) and nodal plane 2 (NP2). For more details see Tables S2 and S3.
Discussion

- While co-seismic rupture properties do not vary with distance from the top of the slab, we observe clear differences in the post-seismic activity pattern, with a decrease of the aftershocks as the distance from the top of the slab and temperature increase (700-750 °C isotherm-depths).

- E1 is located 7 km from top of slab, close to the oceanic Moho (Fig. 1b), and its aftershocks locations delineate a potential pre-existing fault aligned and similar to those extensional faults located in the outer-rise region. These tensional faults are likely caused by plate bending, and provide a pathway for fluid infiltration, producing hydration into the crust and uppermost mantle (Boneh et al., 2019; Contreras-Reyes et al., 2008; Iyer et al., 2012).

- Previous studies in the DSZ of this region (Dorbath et al., 2008) observed that the upper seismicity layer (USL) corresponding to oceanic crust, is characterized by intermediate Vp (~7.7 km/s) and low Vp/Vs (1.67) values, concluding that the USL is related to fluid releases associated with metamorphic reactions.
Discussion

• We observe a dominant **tensinal stress regime**, where mainshocks with normal focal mechanism occur up to 40 km from the top of the slab. This isotherm-depth interval is much deeper than the expected depth for this type of focal mechanism, where that the transition from tensional to compressional regime (neutral plane) occurs along the **400-450 °C isotherm-depth** (Seno & Yamanaka, 1996).

• Seismic tomographic studies in Chilen (Contreras-Reyes et al., 2008) and Nicaragua outer-rise regions (Lefeldt et al., 2009) show a **reduction in the upper oceanic mantle velocities**, in a region between the outer and inner trench wall, and which is matching with the same isotherms (400-450 °C).

• These isotherm-depths were interpreted as the **lower limit for hydro-alteration** within the upper part of the oceanic lithosphere, where extensional stresses dominate, and fluids may not be able to penetrate any deeper than neutral plane.
Discussion

- Northern Chile corresponds to the region where the oceanic Nazca plate is relatively old and therefore colder and with a deep fragile-ductile system with an age of 54 Ma closest to the trench (Müller et al., 2008) and 58 Ma estimated for the area where the mainshocks occur.

- A plausible mechanism for neutral plane deepening in northern Chile would be the increase in bending stresses due to a greater slab-pull associated to the relative old, cold and heavier oceanic Nazca plate (50-55 Ma, see Müller et al., 2008).

- In particular, in this zone the largest slab-pull IDE has been registered for the Tarapacá 2005 Mw 7.7 event (Peyrat et al., 2006), and the 1950 Ms 8.0 tensional event (Kausel & Campos, 1992), reflecting the tensional character of the stress field within the subducting slab.

We propose a conceptual model:
(1) In the outer-rise region extensional bend-faulting occur and lead to partial hydration of the crust and upper mantle. However, fluids may not be able to penetrate any deeper than neutral plane (approximately 450 °C isotherm-depth). Thus, the neutral plane separates a high-hydrated from a dry or poorly hydrated zones.
As the oceanic plate subducts, a deepening of the neutral plane occurs by the increase of the slab-pull forces, separating it from the 450 °C isotherm, and increasing the region subject to extensional failure.
Normal (tensional) events occur at different distances from the top of the slab, but their behavior is mostly controlled by variable physical background conditions. In particular, in the high-hydrated region a greater number of aftershocks is observed, differently from what is observed in the dry deeper zone.
Conclusions

• Our results show that, although of these events are located at different depths and under different thermal conditions, all have similar rupture physics, with analogous geometries considering an elliptical-patch.

• On the other hand, a clear decrease of the number of aftershocks as the distance from the top of the slab and temperature increase is observed.

• We propose that this behavior could be controlled by the incoming plate hydration, where the 400 – 450 ºC isotherm-depths and neutral plane acts as limits for hydration in the outer-rise region, which is deepened by the slab-pull as the slab subducts.
Acknowledgments

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