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Depth-Dependent Recurrence and Slip-Rate Behavior of Repeating Earthquakes in Northern Chile

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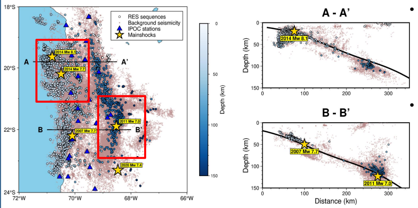
Abstract

Repeating earthquakes provide constraints on fault slip and loading processes along subduction zones. We analyze a comprehensive repeating earthquake catalog from northern Chile spanning more than two decades (Folesky et al., 2025), consisting of 3153 repeating earthquake sequences with magnitudes ranging from −0.3 to 4.7. These repeating sequences are clustered at two depth ranges: shallow group (<70 km) and intermediate-depth group (70–210 km), spanning from the interface to within the subducting slab.We compare the recurrence behavior and slip-rate response of shallow and intermediate-depth repeating earthquakes. Shallow repeaters show strong sensitivity to large megathrust earthquakes. Following the 2014 Mw 8.1 Iquique earthquake, inferred slip rates accelerated to peak values of up to 47.10 cm/yr, then decayed over approximately five years to a quasi-steady level of 3.3449 cm/yr, and eventually returned toward a background rate of 0.34 cm/yr. In contrast, intermediate-depth repeating earthquakes exhibit little systematic response to large megathrust events.Despite these contrasting responses, both shallow and intermediate-depth repeaters record comparable background slip rates of ~0.5–1.0 cm/yr. Along-strike and space–time analyses further indicate that north–south variability at intermediate depth is expressed primarily in recurrence patterns rather than in slip-rate amplitude. These results demonstrate pronounced depth-dependent differences in repeating earthquake behavior and provide new observational constraints on fault slip processes from the shallow megathrust to intermediate depths.

Repeating Earthquake Sequences (RES) in northern Chile



- Repeating earthquake sequences (RES) are groups of earthquakes with nearly identical waveforms, magnitudes, and locations that repeatedly rupture the same fault patches, driven by surrounding aseismic slip (Uchida & Bürgmann, 2019).
- In the Northern Chilean subduction zone, RES are detected from the shallow to intermediate-depth, offering a unique opportunity to characterize depth-dependent RES behavior.

Figure 1. Mapview and cross-sections of the Northern Chilean subduction zone. RES, background seismicity, IPOC stations and M7+ mainshocks are denoted by red and gray circles, blue triangles, and yellow stars, respectively. Red boxes represent the subregions where further analyses were conducted.

Motivations/ Research Questions

- *Do shallow and intermediate-depth RES show different slip rate histories following the mainshock? If so, what do these differences reveal about their surrounding loading conditions?*
- *Do Northern Chile RES scale with Nadeau & Johnson (1998) scaling laws?*

Northern Chile RES & Seismicity Catalog

- The RES catalog of Folesky et al. (2025) and background seismicity catalog of Sippl et al. (2023) for the Northern Chilean subduction zone are used, both partitioned into shallow (0–80 km) and intermediate-depth (80–220 km) populations.
- Mining events are removed from the background catalog, and depth-specific magnitude of completeness (Mc) thresholds are estimated using AEReLU (Wang et al., 2025) and applied to seismicity catalog prior to analysis.

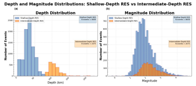


Figure 2. Repeating earthquake sequences in Northern Chile. (a) Depth distribution of shallow (blue) and intermediate-depth (orange) RES. (b) Magnitude distribution of both populations.

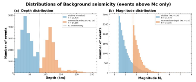


Figure 3. Background seismicity distributions in Northern Chile for shallow (light blue) and intermediate-depth (light orange) populations. (a) Depth distribution. (b) Magnitude distribution showing all events (light shading) and events above the magnitude of completeness (dark shading)

D-Mo Scaling Relationship and Sensitivity Test

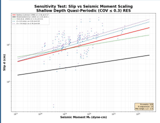


Figure 4. Sensitivity test of the d-Mo scaling relationship for shallow quasi-periodic RES (COV ≤ 0.3) in Northern Chile, following the methodology of Chen et al. (2020).

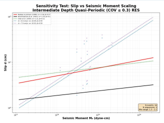


Figure 5. Sensitivity test of the d-Mo scaling relationship for intermediate quasi-periodic RES (COV ≤ 0.3) in Northern Chile, following the methodology of Chen et al. (2020).

- In Northern Chile RES catalog, slip per event was estimated using Nadeau & Johnson (1998): log d = α + β log M_0 (α = −2.36, β = 0.17).
- However, NJ98 was calibrated at Parkfield, which differs in tectonic setting and loading rate from Northern Chile, necessitating a sensitivity test.
- Slip rate varied from 1.0–8.0 cm/yr following Chen et al. (2020); fitted α and β compared against Nadeau & Johnson (1998) and Khoshmanesh et al. (2015) as bounding references.

Shallow-Depth RES

Shallow RES d–M_0 pairs fall within the NJ98–K15 bounds across all tested slip rates, with best-fit regressions consistent with 6.0–7.0 cm/yr and overlapping the geodetic loading rate of 6.7 cm/yr, supporting the use of NJ98 for shallow slip estimation.

Intermediate-Depth RES

Intermediate-depth RES exhibit a steeper scaling slope (β = 0.59) with d–M_0 pairs plotting largely above the NJ98 upper bound, suggesting a distinct slip scaling regime at depth where NJ98 may not be directly applicable

Spatiotemporal Variation Patterns and Slip Rate Analysis

Shallow-Depth RES

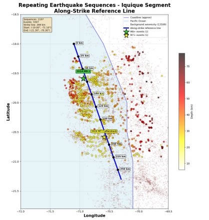


Figure 6. Map of the 2014 Mw 8.1 Iquique segment showing the spatial distribution of 917 shallow RES (colored circles, depth-coded) and background seismicity (gray dots) along a 269 km along-strike reference line. The 2014 Mw 8.1 mainshock and 2014 Mw 7.7 aftershock epicenters are indicated by green and yellow stars, respectively.

- To characterize the depth-dependent post-seismic response of RES, spatiotemporal slip and seismic moment (Mo) heatmap diagrams, along with background seismicity rate changes, are computed for both shallow and intermediate-depth regimes.
- Slip rate analysis and cumulative slip comparisons between RES and background seismicity are constructed to capture post-seismic peak slip rate, and whether slip acceleration is accompanied by elevated aftershock rates.

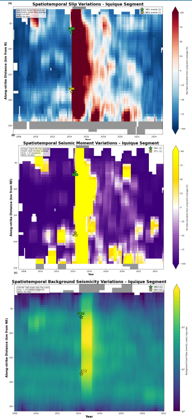


Figure 7. Space-time diagrams of the 2014 Mw 8.1 Iquique segment (20 km bins, 1-year trailing window, 20 km spatial smoothing). (a) Along-strike slip rate variations, where red and blue denote above- and below-average slip rates, respectively. (b) Seismic moment rate (Mo) deviations from the long-term segment average, where yellow and violet indicates elevated and moment release, respectively. (c) Background seismicity rate variations for the same segment and time period.

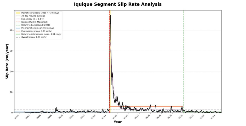


Figure 8. Slip rate analysis for the 2014 Mw 8.1 Iquique segment, normalized by the total number of RES sequences and smoothed using a 30-day moving average. The pre- and post-seismic background slip rates are indicated by blue and orange horizontal lines, respectively, and the exponential decay fit is shown as a dotted curve.

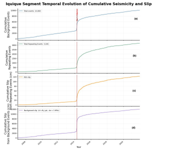


Figure 9. Cumulative time series for the 2014 Mw 8.1 Iquique segment showing (a) background event count, (b) repeating event count, (c) cumulative slip from RES, and (d) cumulative slip estimated from background seismicity. The red dashed line marks the 2014 Mw 8.1 mainshock.

Shallow-depth RES exhibits post-seismic slip acceleration following the 2014 Mw 8.1 Iquique mainshock, accompanied by a concurrent increase in background seismicity rate while slowly decaying for approximately 2 years.

Intermediate-Depth RES

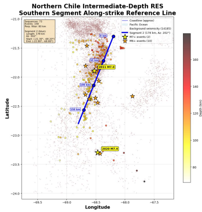


Figure 10. Map of the southern segments, showing the spatial distribution of 73 ID RES (colored circles, depth-coded) and background seismicity (gray dots) along a 178 km along-strike reference line. The 2011 Mw 7.0 mainshock and the M6 events are indicated by yellow and orange stars, respectively.

- Afterslip as driving mechanism is not evident at this depth range.

Do intermediate-depth RES follow the same scaling framework? see the next section.

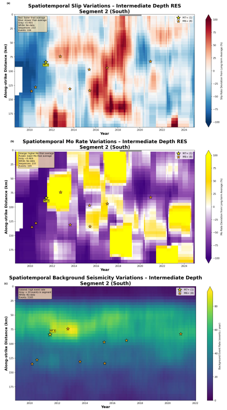


Figure 11. Spatiotemporal diagrams of the 2011 Mw 7.0 segment at intermediate depth (20 km bins, 1-year trailing window, 20 km spatial smoothing). (a) Along-strike slip rate variations, where red and blue denote above- and below-average slip rates, respectively. (b) Seismic moment rate (Mo) deviations from the long-term segment average, where yellow and violet indicates elevated and moment release, respectively. (c) Background seismicity rate variations for the same segment and time period.

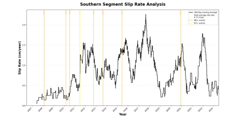


Figure 12. Slip rate analysis for the 2011 Mw 7.0 ID southern segment, normalized by the total number of RES sequences and smoothed using a 180-day moving average. Yellow and orange vertical line denotes the M7 and M6 events, respectively.

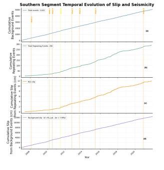


Figure 13. Cumulative time series for the 2011 Mw 7.0, showing (a) background event count, (b) repeating event count, (c) cumulative slip from RES, and (d) cumulative slip estimated from background seismicity. The yellow and orange vertical lines correspond to the M7 and M6 events, respectively.

Intermediate-depth RES show no clear post-seismic acceleration signatures characteristic of shallow interplate afterslip.

Tr-Mo Scaling Relationship

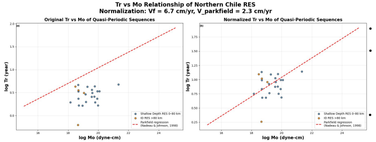


Figure 14. Tr-Mo scaling relationship of Northern Chile quasi-periodic RES for shallow (0–70 km) and intermediate-depth (>70 km) populations. (a) Original recurrence intervals plotted against seismic moment, showing systematic offset below the Parkfield regression line (Nadeau & Johnson, 1998; dashed red). (b) Normalized recurrence intervals following Chen et al. (2007), using V_NC = 6.7 cm/yr and V_Parkfield = 2.3 cm/yr, showing improved agreement with the Parkfield regression line.

Tr-M0 Scaling Relationship

- The logarithm of averaged recurrence intervals (Tr) is plotted against the logarithm of averaged seismic moment (Mo) for both shallow and intermediate-depth.
- Recurrence intervals are normalized by tectonic loading rate following Chen et al. (2007) to account for differences in regional setting between Northern Chile and Parkfield:

$$T_r^{nor} = \frac{V_{NC} \times T_r}{V_{parkfield}}$$

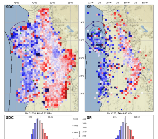
where V_NC ... *m/yr.*

- Following loading rate normalization, Northern Chile RES broadly conform to the Parkfield Tr-Mo scaling relationship (Nadeau & Johnson, 1998), indicating similar mechanisms for their recurrence behavior.

Discussion

Contrasting and shared recurrence behavior of shallow and intermediate-Depth RES

- **Shallow-depth RES:** located primarily along the subduction interface, show strong sensitivity to major megathrust events (acceleration of RES activity following the mainshocks). Our observations strongly suggest that shallow repeaters are controlled by transient postseismic loading, primarily driven by afterslip on velocity-strengthening portions of the megathrust.
- **Intermediate depth RES:** show little systematic response to large megathrust earthquakes and a higher proportion of quasi-periodic behavior and weaker clustering of burst-type recurrence. These observations suggest that transient coseismic and postseismic stress perturbations play only a limited role at depth, and that recurrence is instead governed by more stable loading conditions within the slab.
- This difference likely reflects contrasting hosting environments for shallow and intermediate depth RES:
Shallow repeaters occur on the plate interface where loading is strongly modulated by coseismic stress transfer and afterslip, whereas intermediate-depth repeaters occur within mechanically distinct intraslab shear zones, where brittle asperities are embedded within a ductilely deforming slab interior. Following Zhai et al. (2023), we suggest that inherited fault zones, long-term fluid infiltration, and dehydration-assisted weakening provide favorable conditions for repeated brittle failure at intermediate depth, while recurrence is primarily controlled by steady slab-internal loading rather than transient megathrust afterslip.



Possible mechanism inferred for intermediate-depth RES

Recent results from Jonas et al. (2024) show that stress drop increases systematically with depth and magnitude for seismicity in this study area (Figure 15).
At intermediate depth, higher stress drop may explain the less infleunce from nearby large earthquakes. Dehydration assisted weakening enables brittle failure at such depth, whereas ductile creep around the brittle asperities supplies the effective loading rate that controls recurrence. The observed Tr−M0 scaling therefore favors a size dependent effective loading rate, rather than a stress drop scaling inherited from the broader intermediate-depth seismicity.
For intermediate-depth repeaters, dehydration likely explains why brittle repeating failure is possible, but ductile creep around the asperities more likely explains why their recurrence follows the same Tr∝M0^1/6 scaling.

Figure 15. Spatial stress drop distribution across the Northern Chilean subduction zone estimated using Spectral Decomposition and Spectral Ratio methods, with red and blue indicating relatively higher and lower values, respectively. Bottom panels show corresponding log-normal stress drop distributions spanning ~0.1–100 MPa, reflecting considerable spatial variability across the subduction zone. *(Adapted from Folesky et al., 2024)*

Summary

Spatiotemporal and cumulative slip analyses reveal pronounced postseismic acceleration of shallow repeating earthquake (RES) slip rates following the 2014 Mw 8.1 Iquique mainshock, consistent with afterslip as the primary loading mechanism on the megathrust interface. In contrast, intermediate-depth RES show no comparable postseismic response to nearby large earthquakes, but instead exhibit persistent and episodic recurrence patterns that appear largely independent of major megathrust events.
Although both shallow and intermediate-depth RES follow a similar Tr–M0 scaling, suggesting comparable recurrence scaling across depth ranges, their physical controls are likely different. For shallow RES, recurrence is strongly modulated by transient aseismic slip associated with coseismic and postseismic stress transfer. For intermediate-depth RES, the absence of large-earthquake sensitivity suggests that recurrence is governed by more stable slab-internal loading, potentially within dehydration-assisted weak zones embedded in a ductile shear environment.
Furthermore, the observed d–M0 scaling indicates that intermediate-depth RES may operate under distinct rupture physics, consistent with the broader stress-drop variability characteristic of intermediate-depth seismicity.
The d–M0 scaling further highlights this contrast. Shallow quasi-periodic RES (COV≤0.3) are consistent with the classical Nadeau and Johnson (1998) relation and best-fit loading rates of ~6–7 cm/yr, close to the geodetic convergence rate of 6.7 cm/yr, supporting the applicability of the standard asperity-loading model at shallow depth. In contrast, intermediate-depth RES exhibit systematically steeper ddd–M0M_0M0 scaling and plot above the NJ98 upper bound, indicating a distinct slip scaling regime at depth where the classical shallow-fault formulation may no longer apply directly. This behavior suggests different rupture physics and is consistent with the broader stress-drop variability characteristic of intermediate-depth seismicity.

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