



## RESEARCH LETTER

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## Key Points:

- Seismic and aseismic slips on the southern end of the Ghazaband fault
- At least 1 year of afterslip with 70% of the coseismic moment release
- Smaller earthquakes have a higher aseismic relative to seismic moment release

## Supporting Information:

- Figures S1–S4 captions and Table S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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## Coseismic and postseismic deformation due to the 2007 *M*5.5 Ghazaband fault earthquake, Balochistan, Pakistan

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**Abstract** Time series analysis of interferometric synthetic aperture radar data reveals coseismic and postseismic surface displacements associated with the 2007 *M*5.5 earthquake along the southern Ghazaband fault, a major but little studied fault in Pakistan. Modeling indicates that the coseismic surface deformation was caused by ~9 cm of strike-slip displacement along a shallow subvertical fault. The earthquake was followed by at least 1 year of afterslip, releasing ~70% of the moment of the main event, equivalent to a *M*5.4 earthquake. This high aseismic relative to the seismic moment release is consistent with previous observations for moderate earthquakes ( $M < 6$ ) and suggests that smaller earthquakes are associated with a higher aseismic relative to seismic moment release than larger earthquakes.

### 1. Introduction

Since 1892 four  $M > 7$  earthquakes ruptured the western India plate boundary [Ambraseys and Bilham, 2003], the latest one being the 2013 *M*7.7 earthquake [Avouac et al., 2014; Barnhart et al., 2014; Jolivet et al., 2014b]. The Ghazaband fault, one of the main structures of the western India plate boundary zone, is a possible source of the *M*7.7 1935 earthquake which devastated the city of Quetta causing up to 35,000 fatalities [Lawrence et al., 1981; Ambraseys and Bilham, 2003; Szeliga et al., 2012].

Geodetic observations of strain accumulation and release can help to better understand the nature of the Ghazaband fault and the earthquake hazard of Balochistan. Here we report interferometric synthetic aperture radar (InSAR) observations of the coseismic and postseismic deformation associated with the *M*5.5 earthquake of 19 October 2007. We estimate the ratio of aseismic moment release by afterslip relative to the coseismic moment release and compare the ratio with other earthquakes with reported observations of afterslip.

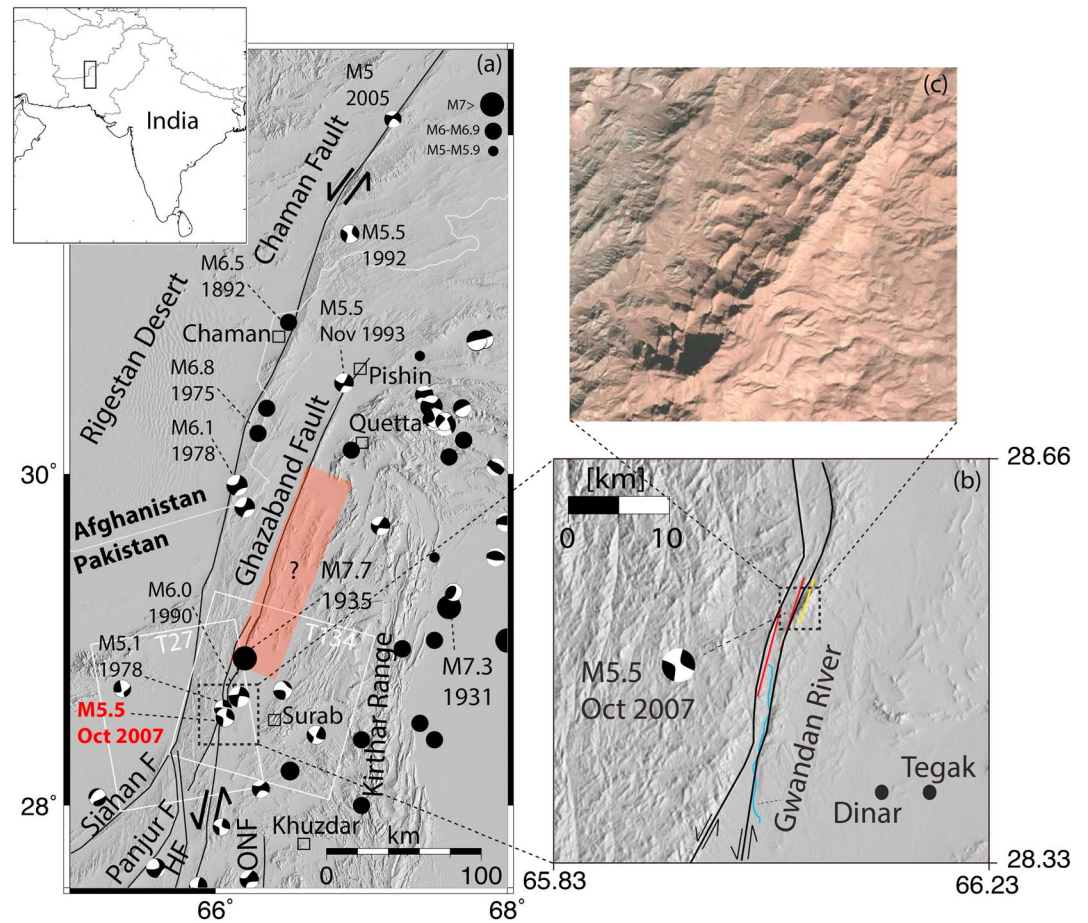
### 2. Tectonic Setting

The Chaman fault system, forming the transform to transpressive boundary between the India and Eurasia tectonic plates, consists of a group of sinistral strike-slip faults including the Ornach Nal, Ghazaband, and Chaman faults (Figure 1a). To the south, the Chaman fault connects with the faults of the Makran ranges (Siahan, Panjgur, and Hoshab faults), which accommodate both the shortening due to the convergence of Arabia and Eurasia and the shear between India and Eurasia. The Ghazaband fault runs for about 300 km roughly parallel to the Chaman fault.

Szeliga et al. [2012] report velocities from a sparse campaign GPS network at latitudes 30–32°N. Their stations KACH and CHMC suggest ~12 mm/yr relative velocity across the combined Chaman and Ghazaband fault systems. However, plate motion models suggest 26 mm/yr fault-parallel and 5–8 mm/yr fault-normal motion between the Indian and the Eurasian plates [Szeliga et al., 2012].

Four moderate earthquakes ( $5 < M < 6$ ) with predominantly strike-slip focal mechanisms occurred in 1975, 1978, 1990, and 2007 in the southern Ghazaband fault area near latitude 28.5°N (Figure 1a). In 1993 a *M*5.5 earthquake ruptured the northern Ghazaband fault near the city of Pishin [Szeliga, 2010]. These earthquakes are evidence that the fault accommodates a portion of the deformation.

The Global centroid moment tensor (CMT) and U.S. Geological Survey solutions place the 19 October 2007 event 15 km northeast of the observed ground deformation likely due to location error given the poor

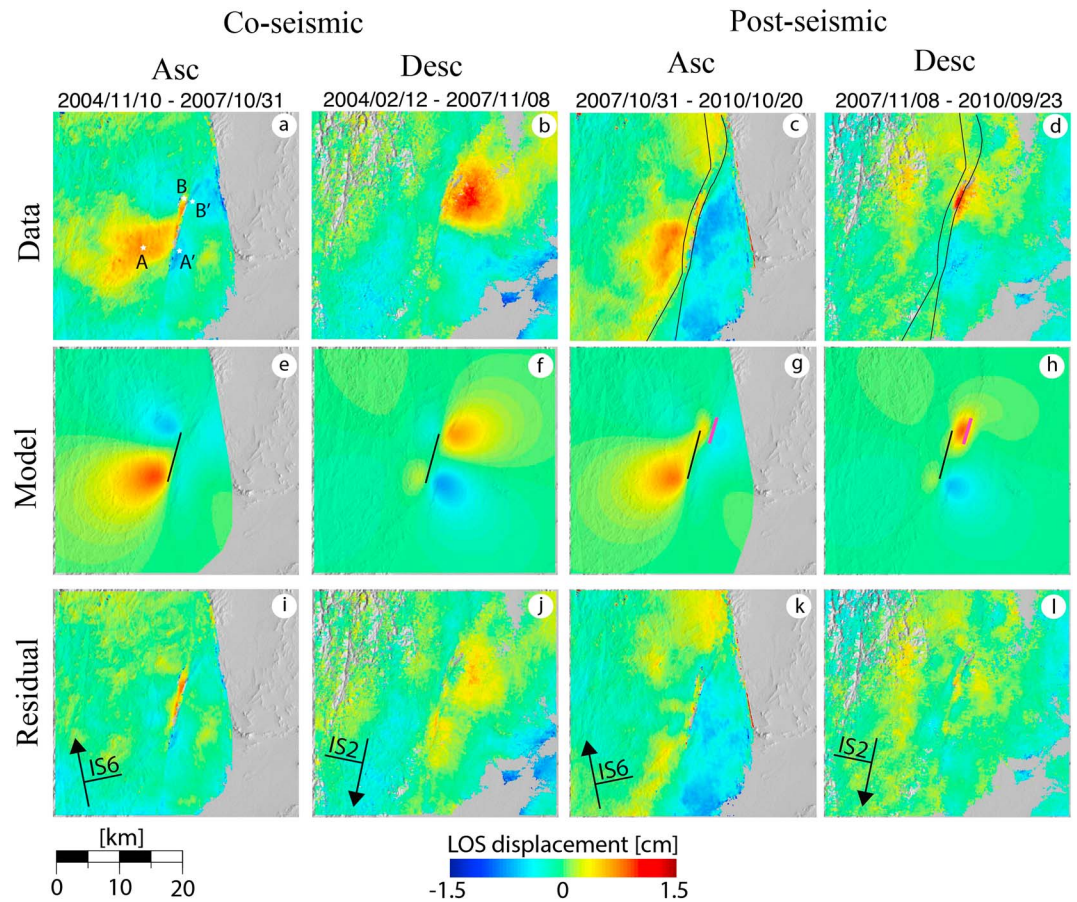


**Figure 1.** (a) Location map of the Ghazaband fault. Solid white rectangles: footprint of ascending and descending frames. Black circles show the 1982–1976,  $M > 5$  earthquakes from *Ambraseys and Bilham* [2003]. Focal mechanisms are from the Global CMT catalog. Locations of  $\sim M7.7$  1935 Quetta earthquake and  $M6.1$  1978 Nushki earthquake on Chaman fault are from *Engdahl and Villaseñor* [2002] and location of  $M5$  2005 earthquake on Chaman fault north of Chaman city is adjusted from *Furuya and Satyabala* [2008]. Faults at latitude  $< 29^\circ\text{N}$  are from *Lawrence et al.* [1981] and for  $> 29^\circ\text{N}$  derived from Google Earth imagery. Orange shaded rectangle: possible location of 1935 rupture. HF and ONF stand for Hoshab Fault and Ornach Nal Fault, respectively. (b) Zoom into epicentral area of the  $M5.5$  October 2007 earthquake. Red lines are strike-slip dislocations, yellow line is reverse-slip dislocation, and blue line is the Gwandan River. (c) Optical imagery from Google Earth of the mountain range overlying the reverse-slip dislocation (see text).

resolution of global seismic networks [Weston et al., 2011]. The earthquake was followed by a  $M3.9$  aftershock 1 day later. The topography of the epicentral region and Google Earth imagery suggests for this latitude a system of two subparallel faults (Figure 1b).

### 3. Data Analysis and Results

We use 2004–2010 ascending (beam IS6) and descending (beam IS2) Envisat advanced synthetic aperture radar (ASAR) data from tracks 27 and 134 to investigate the coseismic and postseismic ground deformation due to the 2007 earthquake using InSAR time series analysis. We use the Jet Propulsion Laboratory/Caltech ROI\_PAC software [Rosen et al., 2004] for processing interferograms with perpendicular baselines less than 200 m. We invert the network of interferograms (supporting information Figure S1) for the phase history [Berardino et al., 2002] and then correct for the local oscillator drift of the ASAR instrument [Marinkovic and Larsen, 2013; Fattahi and Amelung, 2014], for topographic residuals [Fattahi and Amelung, 2013] and for the stratified tropospheric delay [Jolivet et al., 2014a] using the ERA-Interim global atmospheric reanalysis model [Dee et al., 2011]. From the corrected



**Figure 2.** (a, b) Coseismic and (c, d) postseismic LOS displacement maps obtained from the time series for the Ghazaband fault earthquake from ascending and descending Envisat satellite tracks (IS6 and IS2 beams, respectively). (e–h) Predicted LOS displacements from the best fitting models. Black and pink lines are modeled strike-slip and dip-slip displacements, respectively. (i–l) Differences between the best fitting models and the observations (residuals). Arrows show satellite flight directions, and black bars show the look directions. The location is given by Figure 1b.

InSAR time series we reconstruct the coseismic and postseismic displacements without any assumption about the spatial or temporal deformation model.

Coseismic ground displacement maps in radar line-of-sight (LOS) direction between 2004 and 12 and 20 days after the earthquake obtained from the ascending and descending displacement histories show the ground deformation during and in the first days after the earthquake (Figures 2a and 2b). We present displacements since 2004 because these early acquisitions are characterized by smaller lateral tropospheric delay variations. The ascending LOS displacement map shows the typical quadruple displacement pattern of strike-slip earthquakes. The displacement toward the satellite in the southwestern lobe (positive LOS, red colors, Figure 2a) and away from the satellite in the northeastern lobe (negative LOS, blue colors) is consistent with left-lateral displacement along a NNE trending fault, similar for the descending data, but the displacement lobes have opposite signs.

Postseismic displacement maps for the subsequent 3 year period show similar deformation patterns, suggesting afterslip with sign and magnitude comparable to the coseismic slip. This is further supported by the similarity of the east-west and vertical displacement patterns inferred from combination of the ascending and descending data (Figure S2). However, the postseismic vertical displacement field shows a notable difference in the elongated uplift in the northeast (Figure S2d), which is referred to in the following as the northeastern uplift. This uplift is likely due to afterslip rather than poroelastic deformation, which would result in ground subsidence [Peltzer *et al.*, 1998; Fielding *et al.*, 2009].

**Table 1.** Best Fitting Model Parameters for the Coseismic and Postseismic Displacements<sup>a</sup>

Fault Number	Longitude	Latitude	Length (km)	Width (km)	Depth (km)	Strike	Dip	Strike Slip (cm)	Dip Slip (cm)	<i>M</i>	Total <i>M</i>
<i>Coseismic</i>											
1	66.03	28.50	7.7 ± 0.8	8.0 ± 2	1.7 ± 0.4	15°	−90°	9.0 ± 2	0	5.48 ± 0.03	5.48 ± 0.03
<i>Postseismic</i>											
1	66.03	28.50	8.8 ± 0.5	6.0 ± 1.2	1.3 ± 0.3	15°	−90°	7.0 ± 1	0	5.35 ± 0.02	5.4 ± 0.02
2	66.06	28.53	4	4	2	17.9°	−83° ± 2.6°	0	3.0 ± 1	4.8 ± 0.01	

<sup>a</sup>The uncertainties were derived from the posterior density distribution of the fault parameters obtained from the Gibbs sampling algorithm (see supporting information Figures S3 and S4 for the plots of the posterior density distribution). To calculate the moment magnitude, we assume rigidity equal to 3E10 Pa.

#### 4. Modeling

We use uniform dislocations in a homogeneous elastic half-space to infer the fault slip responsible for the surface displacements. Our data set consists of 2500 pixels of the LOS displacements sampled from a uniform grid for each viewing geometry. We use a Gibbs sampling inversion technique to determine the parameters and uncertainties of the dislocations [Brooks and Frazer, 2005].

For the coseismic observations, we consider a single vertical strike-slip dislocation. We fix the location and strike of the fault and invert for the best fitting fault length, width, depth, and displacement of the dislocation. The coseismic observations are best explained by ~9 cm of strike-slip displacement along a ~7.7 km long fault at depth (top of the fault) of ~1.7 km (Table 1).

For the postseismic observations the model consists of a strike-slip dislocation with the location of the coseismic model (fault 1) and a dip-slip dislocation (fault 2). We invert for the displacement, depth, length, and width of fault 1 and for the dip and dip-slip displacement of fault 2. The residual atmospheric noise in the InSAR data and the small displacement signal does not allow to constrain the length, width, and depth of the second dislocation. The moment release from fault 2 is only 7% of the total postseismic moment release (Table 1). The postseismic observations are best explained by ~7 cm left-lateral displacement for fault 1 and by ~3 cm reverse slip along fault 2 at depths of ~1.3 and ~2 km, respectively (Table 1 and Figures 2g and 2h). The marginal posterior density distributions (PDDs) for the estimated fault parameters (supporting information Figures S3 and S4) show that the fault source parameters have roughly Gaussian distributions.

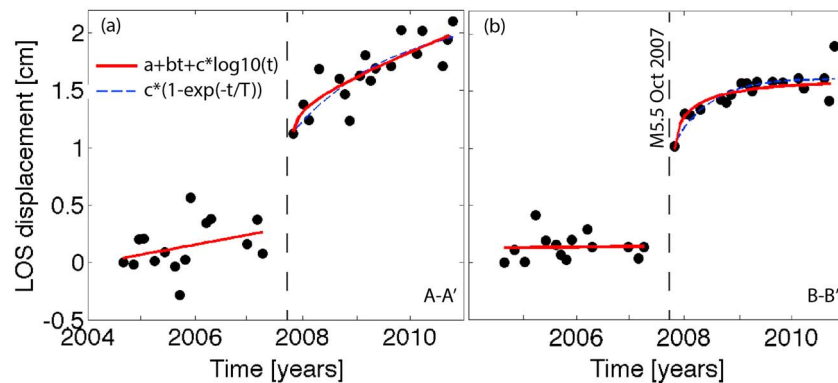
For the coseismic data, the ascending residual map shows a narrow strip of LOS displacement very close to the fault (Figure 2i), which occurs probably because local fault slip variations are not represented by the uniform dislocation. The descending data, which are not sensitive to along-strike fault displacements (the radar looks nearly perpendicular to the fault), do not have such residuals. The residuals in the NE lobe of the descending data (Figure 2j) may be due to early afterslip as it spans eight more days than the ascending data. The residuals in Figure 2k (the blue color at the bottom) are most likely due to the residual tropospheric delay in the data.

#### 5. Discussion

The InSAR data provide insights into a tectonically complex section of the Ghazaband fault system. Coseismic ground deformation was caused by shallow slip along a subvertical, left-lateral, strike-slip fault and postseismic deformation by slip along the same fault as well as by dip slip on a neighboring thrust fault. The geodetic moment magnitude of ~*M*5.5 is consistent with the seismic moment magnitude of *M*5.5 from the Global CMT catalog.

##### 5.1. Shallow Slip

The earthquake was associated with coseismic and postseismic fault slip at shallow depth (~1 to 2 km depth of the model dislocation upper edges). Shallow slip was also observed in the 1993 *M*5.5 earthquake along the northern strand of the Ghazaband fault (focal depth of 2.25 km [Szeliga, 2010]) and in the 2005 *M*5.0 Chaman fault earthquake (maximum slip depth of 2 km [Furuya and Satyabala, 2008]). The 2013 *M*7.7 Balochistan earthquake also largely ruptured near the surface [Avouac et al., 2014], as did several historic earthquakes



**Figure 3.** Relative ascending LOS displacement histories across the fault for (a) the southwestern deformation lobe between points A and A' and (b) the northeastern uplifting area between points B and B' (see Figure 2a for locations), together with the linear fits for the pre-seismic and the logarithmic and exponential fits to the post-seismic data.

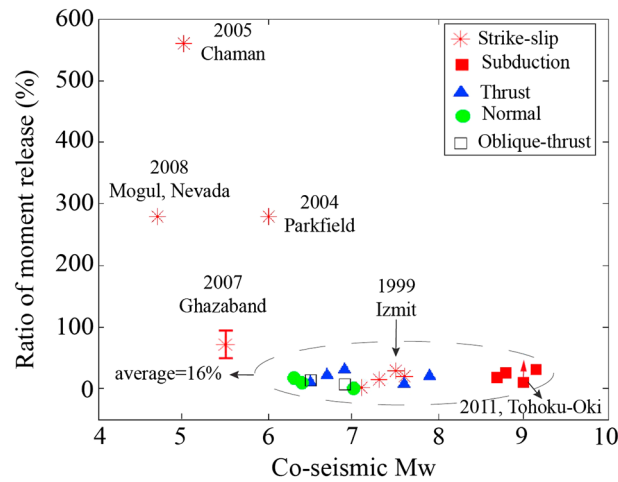
along the Chaman fault [Szeliga *et al.*, 2012]. This could suggest that shallow fault slip is widespread in this plate boundary zone, in contrast to other tectonic settings where some earthquakes may be associated with slip deficits at shallow depth [Fialko *et al.*, 2005; Dolan and Haravitch, 2014]. Shallow slip deficit can be partly explained by shallow creep distributed across the fault during the interseismic period [Kaneko and Fialko, 2011] or by distributed yielding [Lindsey *et al.*, 2014]. Xu *et al.* [2015] suggest that the shallow slip deficit is apparent and an artifact due to interferometric decorrelation near earthquake ruptures. This interpretation is consistent with the presence of shallow slip and high interferometric coherence near the Ghazaband fault trace.

### 5.2. Afterslip

The InSAR data and modeling show that the earthquake was followed by 7 cm of slip along the strike-slip fault and by 3 cm of slip along the shallow thrust fault (Table 1). The LOS displacement histories for the southwestern deformation lobe and for the northeastern uplift area, relative to points on the opposite sides of the fault, show the displacements before, during, and after the earthquake (Figures 3a and 3b). The AA' displacement history is noisier than the BB' displacement history because the distance between the points is larger, and therefore, the difference is more affected by the residual atmospheric delay. The slight slope of less than 0.5 mm/yr of the AA' displacement history is most likely due to the noise of the InSAR data and not due to the interseismic shallow fault creep, as confirmed by the absence of a trend in the less noisy BB' displacement. The afterslip lasted over 2 years in the southeastern area (Figure 3a) and at least 1 year in the northeastern area (Figure 3b). The postseismic displacement histories are well fitted by logarithmic or exponential functions. This 2007 Ghazaband fault earthquake has a ratio of  $70 \pm 10\%$  between postseismic and coseismic moment release, which is a lower bound estimate given that the first 12 days and 20 days of afterslip are included in the coseismic displacement from ascending and descending data, respectively.

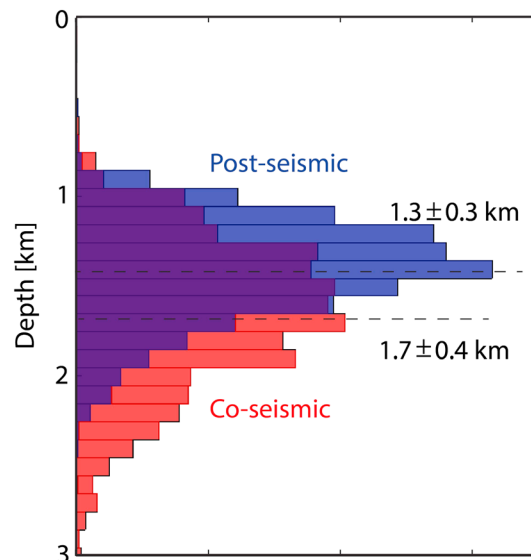
Space-geodetic observations of afterslip over the past two decades provide an opportunity to better understand the nature of afterslip. Afterslip generally surrounds the high-slip patches of the coseismic rupture [Marone *et al.*, 1991; Perfettini and Avouac, 2007] and has been observed following strike-slip [Freed, 2007; Furuya and Satyabala, 2008; Hearn *et al.*, 2009], thrust [Podgorski *et al.*, 2007], and normal crustal earthquakes [Hamiel *et al.*, 2012], following subduction earthquakes [Miyazaki *et al.*, 2004; Hsu *et al.*, 2006; Sun *et al.*, 2014] and following a detachment fault earthquake [Owen and Bürgmann, 2006].

Figure 4 shows the ratio of the aseismic moment release by afterslip relative to the coseismic moment release for 22 earthquakes in different tectonic settings (references are in Table S1). The  $\sim 70\%$  ratio for the M5.5 on the Ghazaband fault falls below the ratios of 500%, 280%, and 300% for the M5 2005 Chaman fault, the M6 2004 Parkfield, California, and the M4.7 2008 Mogul, Nevada, earthquakes, respectively [Freed, 2007; Furuya and Satyabala, 2008; Bell *et al.*, 2012], and above the ratios of 15%, 2%, and 29–32% for the M7.3 1992 Landers, M7.1 1999 Hector Mine, and M7.5 1999 Izmit, Turkey, earthquakes, respectively [Shen *et al.*, 1994; Jacobs *et al.*, 2002; Wang *et al.*, 2009]. The distribution shows that moderate earthquakes ( $M < 6$ ) are



**Figure 4.** Ratio of aseismic moment release by afterslip relative to the coseismic moment release for earthquakes with reported afterslip (see supporting information Table S1). The red bar for the Ghazaband earthquake shows the  $2\sigma$  uncertainty. The red arrow for the 2011 Tohoku-Oki earthquake indicates that afterslip still continues and the ratio will increase with future observations.

than the coseismic dislocation (means of 1.3 and 1.7 km, respectively, Figure 5). This, together with the smaller width of the postseismic dislocation (6 km for the postseismic versus 8 km for the coseismic dislocation, Table 1), suggests that the afterslip was generally shallower than the coseismic slip, consistent with the narrower spatial pattern of the postseismic (Figure S2b) compared to the coseismic surface displacements (Figure S2a). The shallower depth of afterslip is consistent with inferred velocity-strengthening behavior along the shallow parts of faults related to a lower degree of sediment consolidation [Scholz, 1998; Wei *et al.*, 2013]. However, the small difference between the depths of the coseismic and postseismic dislocations (Figure 5) suggests possible overlap between the coseismic and postseismic patches. The overlap of the coseismic and postseismic regions can represent conditionally stable frictional behavior of the shallower parts of the fault with coseismic slip nucleated on velocity-weakening asperities at depth and propagated to the conditionally stable regions, which can also slip aseismically [Scholz, 1998; Noda and Lapusta, 2013]. However, the small surface displacement signal does



**Figure 5.** Marginal posterior density distribution for the depth of coseismic (red) and postseismic (blue) dislocations.

followed by proportionally more aseismic moment release than large earthquakes ( $M > 6$ ). This difference could reflect that large earthquakes produce a more complete stress drop than smaller ones, and thus, proportionally less elastic strain energy remains stored in the crust. We note that these ratios have to be interpreted with caution because many studies lack continuous geodetic observations immediately after the earthquake and because afterslip may continue for many years at a decaying rate such as for the Izmit earthquake [Çakir *et al.*, 2012].

### 5.3. Depths of Coseismic Slip and Afterslip

The PDDs of the depths of the upper edge of the dislocations estimated using the Gibbs sampling approach show that the postseismic dislocation is slightly shallower

not allow to infer the spatial variation of slip at depth, and thus, we cannot rule out an alternative scenario of lateral variations in frictional behavior with seismic movements of velocity-weakening patches and aseismic movements of velocity-strengthening patches [e.g., Hsu *et al.*, 2006].

### 5.4. Postseismic Push-Up

The reverse-slip dislocation explaining the postseismic uplift is located under a ~7 km long unnamed mountainous ridge subparallel to the Ghazaband system (Figure 1b). The ridge is the highest topographic expression in the area (with elevation of ~300 m above the surroundings). The spatial match with the detected uplift suggests that the ridge may have been created by repeated push-ups similar to the 2007 event. Inspection of optical remote sensing imagery (Google Earth imagery) shows that the ridge is the only location in the region where inclined sedimentary strata are exposed at the surface (Figure 1c). This

suggests erosional unroofing of recent uplift and that the ridge is the geomorphic expression of the contractional deformation associated with a restraining stepover of the Ghazaband fault system and/or transpressional tectonics.

## 6. Conclusions

Modeling the InSAR observations for the M5.5 October 2007 earthquake on the southern end of the Ghazaband fault suggests that the coseismic slip was produced by ~9 cm of left-lateral displacement on a shallow subvertical fault. The earthquake was followed by ~7 cm slip above and along the main rupture and by a few centimeters of triggered slip along a nearby thrust fault. The InSAR time series shows that afterslip lasted for at least 1 year and released ~70% of the moment of the main event. This ratio between aseismic and seismic moment release is consistent with previous observations of high aseismic moment release for moderate earthquakes ( $M < 6$ ) and higher than the ratio for larger earthquakes.

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