

RESEARCH LETTER

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Key Points:

- We determine the vertical component of motion on the Hoshab fault using Pleiades stereo imagery
- The 2013 earthquake is typical for the Hoshab fault
- Large earthquakes occur in a distributed fashion across the region

Supporting Information:

- Supporting Information S1
- Table S1

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The 2013 Balochistan earthquake: An extraordinary or completely ordinary event?

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Abstract The 2013 Balochistan earthquake, a predominantly strike-slip event, occurred on the arcuate Hoshab fault in the eastern Makran linking an area of mainly left-lateral shear in the east to one of shortening in the west. The difficulty of reconciling predominantly strike-slip motion with this shortening has led to a wide range of unconventional kinematic and dynamic models. Here we determine the vertical component of motion on the fault using a 1 m resolution elevation model derived from postearthquake Pleiades satellite imagery. We find a constant local ratio of vertical to horizontal slip through multiple past earthquakes, suggesting the kinematic style of the Hoshab fault has remained constant throughout the late Quaternary. We also find evidence for active faulting on a series of nearby, subparallel faults, showing that failure in large, distributed and rare earthquakes is the likely method of faulting across the eastern Makran, reconciling geodetic and long-term records of strain accumulation.

1. Introduction

The 24 September 2013 M_w 7.7 Balochistan earthquake, the only modern large upper crustal earthquake in the southwestern India-Eurasia boundary zone (Figure 1), provides a valuable opportunity for studying the ongoing deformation resulting from the accommodation of the relative motion between India and Eurasia. This strike-slip earthquake is very unusual when compared to other well-studied large continental earthquakes worldwide [Lin et al., 2002; Wright et al., 2004; Oskin et al., 2012; Elliott et al., 2012], in that it ruptured a 225 km long section of the curved and moderately dipping (50–70°N) Hoshab fault [Avouac et al., 2014; Jolivet et al., 2014] while appearing to show consistent and predominantly strike-slip behavior along its entire length, its slip vector rotating dramatically along strike by ~60°. This striking observation and the difficulty of reconciling the largely strike-slip motion with the shortening to the west have led to the suggestion that previous events on the fault must have displayed a different ratio of shortening to strike-slip motion. To explain this atypical faulting behavior, a wide range of hypotheses has been proposed, including (1) dynamic stresses during rupture promoting sustained strike-slip failure on a curved fault in the 2013 event [Avouac et al., 2014; Barnhart et al., 2015], (2) time-varying fault kinematics leading to rupture histories which alternate between pure strike-slip and dip-slip [Avouac et al., 2014; Zinke et al., 2014; Barnhart et al., 2015], (3) bimodal slip behavior on different segments along strike accommodating strain partitioning through time [Barnhart et al., 2015], and (4) a ball-and-socket rigid rotation south of the fault that can also account for the complexity at the fault termination point in the Chaman fault system to the northeast [Barnhart et al., 2014]. These ideas largely arise from the interpretation of surface observations of horizontal displacements determined from optical satellite imagery through visual analysis and digital image matching and from very sparse Global Positioning System (GPS) data [Avouac et al., 2014; Jolivet et al., 2014; Zinke et al., 2014; Barnhart et al., 2014, 2015]. We seek to test these complex ideas by additional constraints from the vertical component of motion on the fault.

2. Tectonic Background

The Hoshab fault that ruptured in the 2013 Balochistan earthquake is part of a kinematic transition zone between subduction of the Ormara oceanic plate beneath Eurasia at ~3 cm/yr in the west [Kukowski et al., 2000; Bilham et al., 2007] and northward motion of the Indian plate with respect to Eurasia at ~3 cm/yr in the east (Figure 1) [Mohadjer et al., 2010; Ader et al., 2012; Avouac et al., 2014; Zinke et al., 2014]. High interseismic coupling [Lin et al., 2015] and several large earthquakes, including the 1945 M_w 8.1 earthquake [Byrne et al., 1992] in the eastern Makran subduction zone, suggest that a large fraction ($\geq 70\%$) of the convergence

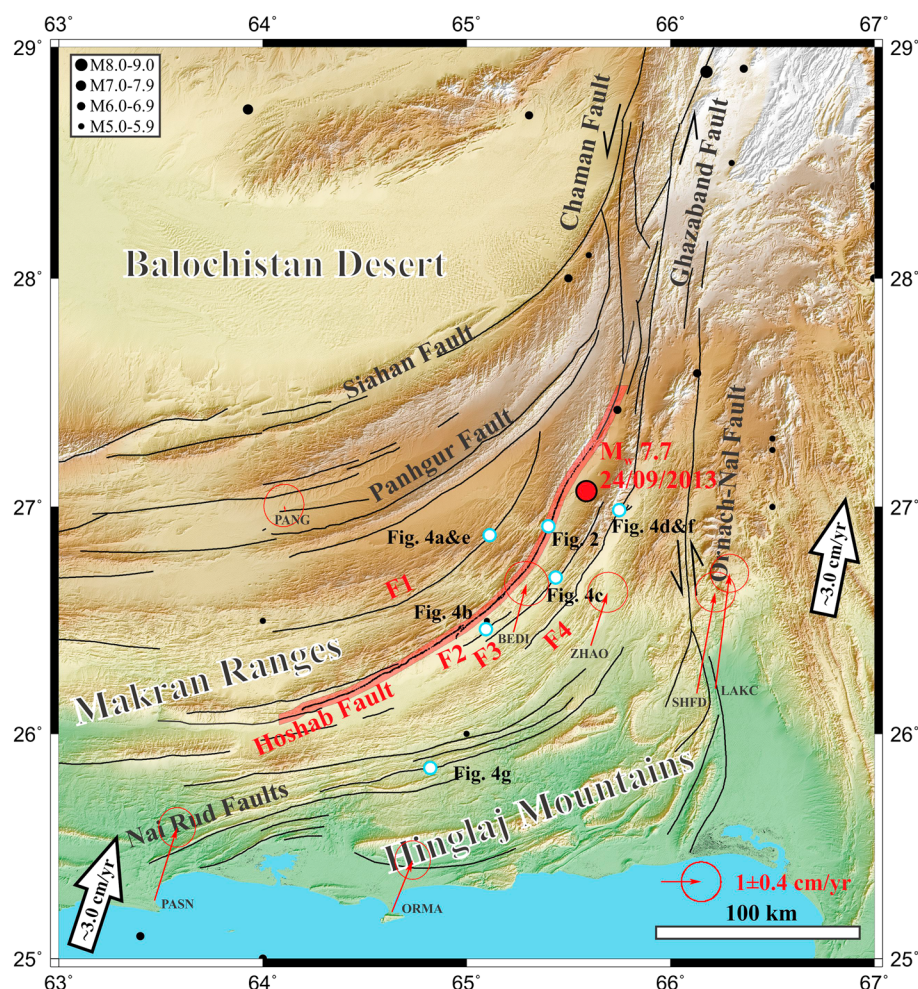


Figure 1. Tectonic setting of the 24 September 2013 Balochistan earthquake. Regional active faults are remapped through our own geomorphic analysis of the landscape. The elongate red polygon denotes the extent of the postearthquake Pleiades stereo imagery (5 km wide $\times$ 240 km long). Red arrows are GPS velocities relative to Eurasia measured at seven campaign sites [Szeliga *et al.*, 2012; Lin *et al.*, 2015]. White arrows indicate relative plate motion. The Arabian oceanic plate subducts beneath Eurasia at ~ 3 cm/yr, and the Indian plate moves northward with respect to Eurasia at ~ 3 cm/yr. F1–F5 are unnamed faults, on which we find evidence for active faulting at the locations indicated by the blue circles. Black dots are historical earthquakes in the region [Song, 2012].

between Arabia and Eurasia is accommodated on the Makran megathrust [Lin *et al.*, 2015]. The rate of shortening to be accommodated by internal deformation in the eastern Makran is uncertain. Deformed river terraces and GPS measurements in the western Makran show a shortening rate of 6–8 mm/yr in the Makran accretionary wedge [Haghipour *et al.*, 2012], about 30% of the rate of convergence, and we use this figure as the rate of shortening for the eastern Makran as well. A recent geodetic study consisting of five GPS sites (Figure 1) reveals ~ 2.5 cm/yr left-lateral motion in the eastern Makran, ~ 1.5 cm/yr of which it is suggested is accommodated on the Ornach-Nal fault [Szeliga *et al.*, 2012]. GPS velocities from stations PANG, BEDI, and ZHAO indicate ~ 1 cm/yr left-lateral motion to be accommodated within the transition zone (Figure 1).

3. Data and Results

3.1. Surface Slip in the 2013 Earthquake

The Pleiades satellite constellation provides 50 cm panchromatic imagery worldwide and allows rapid three-dimensional (3-D) reconstruction due to its stereo capability [Poli and Toutin, 2012]. To quantify the 3-D surface slip, we constructed a high-resolution (1 m) digital elevation model (DEM) from Pleiades stereo imagery for the entire 225 km long surface rupture over an area of more than 1000 km² (Figure 1). By visual analysis of geomorphic features (e.g., Figure 2b), we measured 150 strike-slip offsets (Figure 3) that mainly

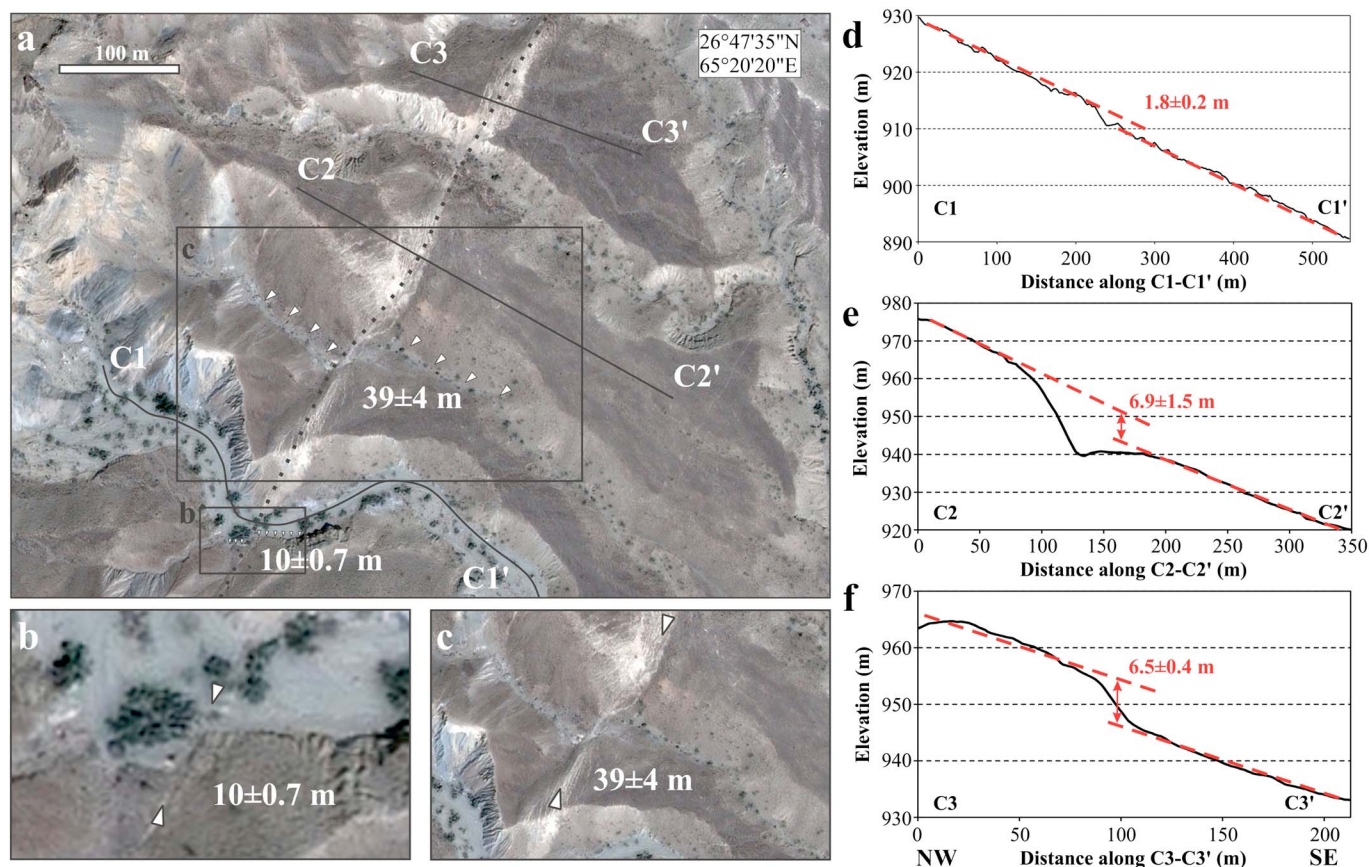


Figure 2. (a) Displacements along the Hoshab fault (see Figure 1 for location). (b) The lateral offset in the 2013 earthquake at this location is 10 m. (c) A gully within an older fan surface is laterally offset by 39 m. (d) Elevation profile C1-C1' from our Pleiades derived 1 m DEM along the old fan surface shows that the vertical displacement in the 2013 earthquake at this location is 1.8 m (north side up). (e) Elevation profile C2-C2' shows a cumulative vertical displacement of 6.9 m (north side up). (f) Elevation profile C3-C3' shows a cumulative vertical displacement of 6.5 m (north side up).

agree well with similar measurements made previously from WorldView imagery [Zinke *et al.*, 2014; Barnhart *et al.*, 2015] and also measurements from subpixel image correlation of preearthquake and postearthquake Landsat 8 images [Avouac *et al.*, 2014]. Where this is not the case is within young alluvial sediments where measurements of the strike-slip offset at the fault are typically less than that seen in image correlations, suggesting that unconsolidated, immature materials do not localize fault slip near the surface [Oskin *et al.*, 2012; Dolan and Haravitch, 2014; Zinke *et al.*, 2014]. In addition, we measured 236 vertical displacements from offset river channels and alluvial fans observed in the postearthquake DEM (Figure 3 and Table S1 in the supporting information). The measurements reveal an average of 1.9 m vertical component of motion, with local maximum up to 5.6 m due to localized bending of the fault trace (Figure S1 in the supporting information). The dominant sense of fault motion is north side-up sinistral-thrusting slip, but some portions of the fault also show south side-up sinistral-normal slip due to rupture complexity and local changes in strike (Figure S2 in the supporting information). Given an average fault dip of $\sim 50^\circ$ N [Avouac *et al.*, 2014; Jolivet *et al.*, 2014], the average shortening in the 2013 event is 1.6 m. We also found a splay from the southern segment of the Hoshab fault to its north (Figure 1), with some indications of vertical motion in the 2013 event (0.6 m and 0.8 m in Figure S10 in the supporting information) where it intersects our Pleiades coverage.

3.2. Cumulative Surface Slip

To test the hypothesis that the kinematics of the Hoshab fault switches between thrust and strike-slip faulting through successive earthquake cycles [Avouac *et al.*, 2014; Zinke *et al.*, 2014; Barnhart *et al.*, 2015], we located six sites in the postearthquake Pleiades imagery and DEM where there is convincing evidence for lateral and vertical displacements accumulated in past earthquakes (Figures 2 and S3–S8 in the supporting information). The cumulative surface slip through multiple earthquakes has a consistent sense with that found for the 2013 earthquake, with a constant local ratio of vertical to horizontal slip (Table S2 in the supporting information).

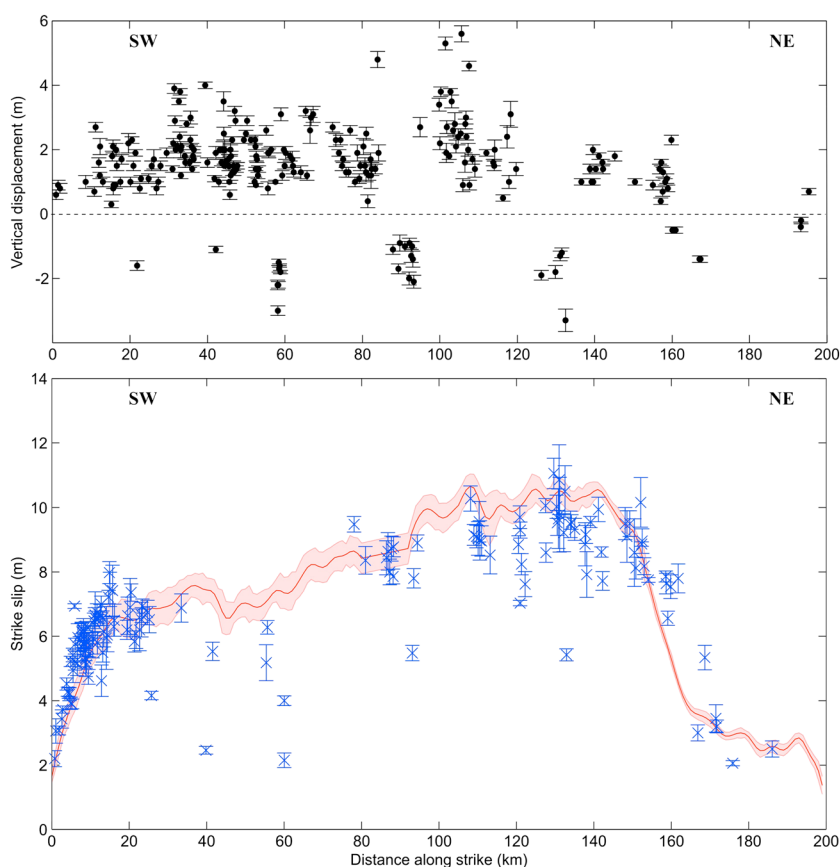


Figure 3. Surface fault slip measured from Pleiades stereo imagery (points) and Landsat 8 image correlation (red band). Black dots show the vertical displacements measured from the Pleiades DEM (positive for north side up; see Table S1 for details). Blue crosses denote the lateral displacements measured by visual analysis of Pleiades imagery (positive for left lateral). Red line and error band is the strike-slip displacement from correlating preearthquake and postearthquake Landsat 8 imagery [Avouac *et al.*, 2014] (positive for left lateral). Some of the scatter in vertical measurements including short sections with south side-up displacements arises from local complexities of bending of the fault trace. We avoided these sections when making our comparisons of short-term and long-term behavior.

For example, a gully in Figure 2c shows a 39 m lateral offset with 7 m north side-up vertical motion, which is approximately four times larger than the slip found for the 2013 earthquake at this location (10 m lateral offset with 1.8 m north side-up vertical motion). An alluvial fan surface is offset by 21 m laterally and 4.3 m vertically (south side up) (Figure S4), which is twice the slip in the 2013 event at this site (10 m lateral and 2.2 m south side-up vertical offsets).

4. Discussion

4.1. Long-Term Fault Kinematics

The occurrence of the 2013 Balochistan earthquake has led to suggestions that the Hoshab fault may accommodate most of the motion between the Makran and India [Avouac *et al.*, 2014; Jolivet *et al.*, 2014; Zinke *et al.*, 2014; Barnhart *et al.*, 2014, 2015]. Assuming that the observed relative motion across the eastern Makran is eventually localized on the Hoshab fault and given an average of 8 m of strike-slip motion (ignoring the ends where slip decreases) and 1.6 m shortening in the 2013 event, it would require an M_w 7.7 earthquake every 800 years to accommodate the 1 cm/yr strike-slip motion [Szeliga *et al.*, 2012] but a much shorter recurrence interval (~200–270 years) if the earthquakes take up the 6 mm/yr shortening in the west [Haghipour *et al.*, 2012; Lin *et al.*, 2015]. It is this shortening deficit that has led to the hypothesis that the kinematics of the Hoshab fault slip switches between thrust and strike-slip faulting in successive earthquake cycles [Avouac *et al.*, 2014; Zinke *et al.*, 2014; Barnhart *et al.*, 2015]. However, our observations of the constant local ratio of vertical to horizontal slip along the fault through multiple past earthquakes indicate that the Hoshab fault has maintained the same style of faulting in the late Quaternary. Cumulative displacements are multiples (2, 4, 5, 6,

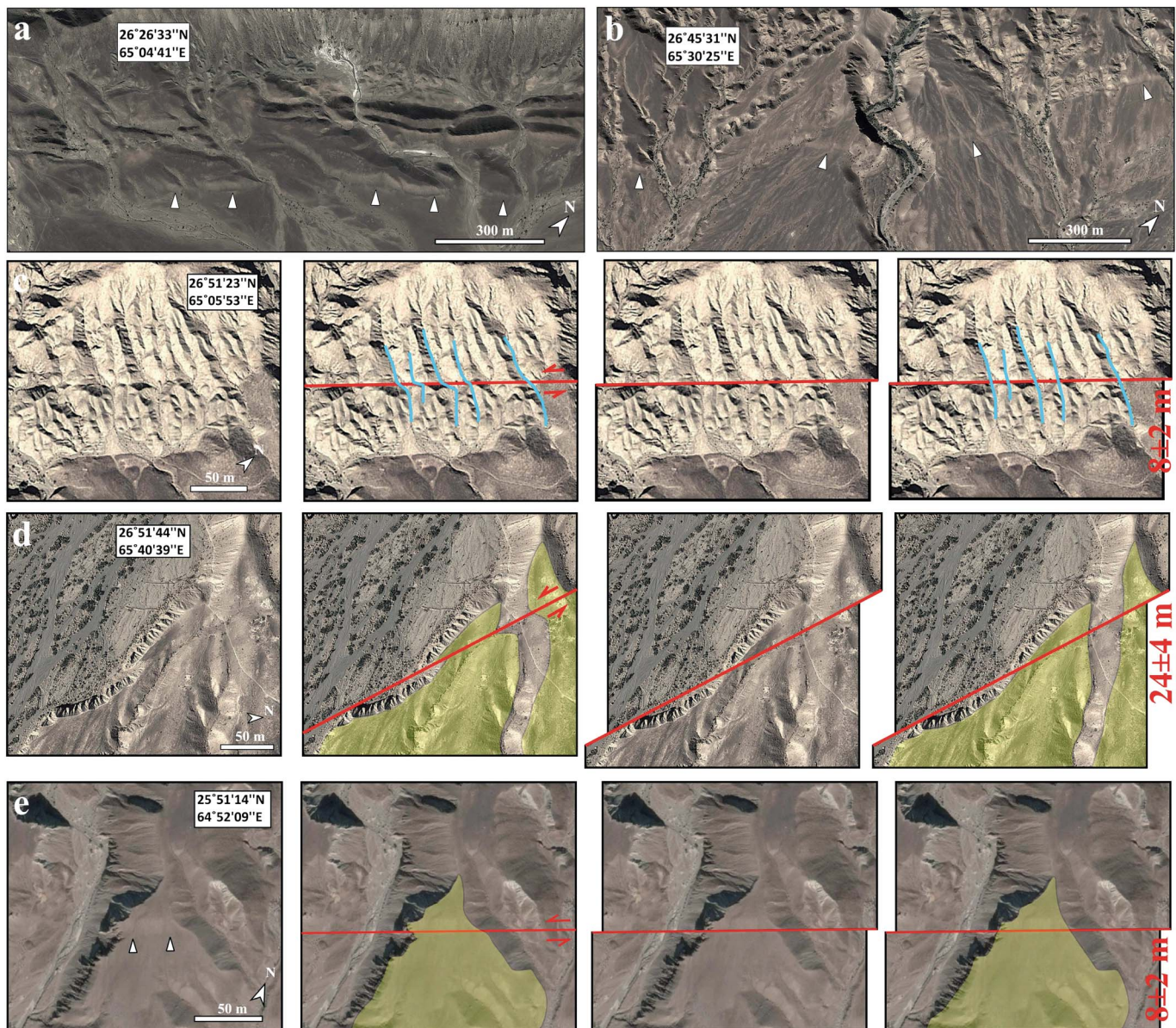


Figure 4. Google Earth imagery showing preserved fault scarps (indicated by white arrows) and lateral offset on faults subparallel to the Hoshab fault (see Figure 1 for location). Preserved fault scarps on (a) F2 and (b) F3. (c) The 8 m lateral offset from restoring the gullies (blue lines) on F1 is of similar magnitude to the surface slip in the 2013 Balochistan earthquake. (d) An alluvial fan surface on F4 was offset by 24 m. (e) An alluvial fan surface on F5 was offset by 8 m. Locations of additional examples are presented in Figure S9.

and 12 times) of the 2013 slip (Table S2), suggesting that this fault may have experienced characteristic slip behavior [Klinger *et al.*, 2003, 2011].

4.2. Distributed Faulting in the Eastern Makran

Previous arguments on the long-term fault kinematics [Avouac *et al.*, 2014; Zinke *et al.*, 2014; Barnhart *et al.*, 2015] suppose deformation is concentrated on the Hoshab fault. We remapped active faults in the eastern Makran [Lawrence *et al.*, 1981] through an analysis of the landscape using satellite imagery and topography and found preserved fault scarps and lateral displacements in old alluvial fans and gullies on a series of regional faults (F1–F5) subparallel to the Hoshab fault (Figures 4 and S9 in the supporting information). We did not observe any fault scarps in the youngest generation of alluvial fans on any of the faults, which was also the case for the Hoshab fault until 2013; in eastern parts of Iran, the youngest generation of alluvial fans are typically 8–10 kyr in age [Walker and Fattahi, 2011], suggesting that the last event on these faults may have occurred >8 kyr ago. The tectonic setting of these subparallel faults F1–F5 is similar to the Hoshab fault

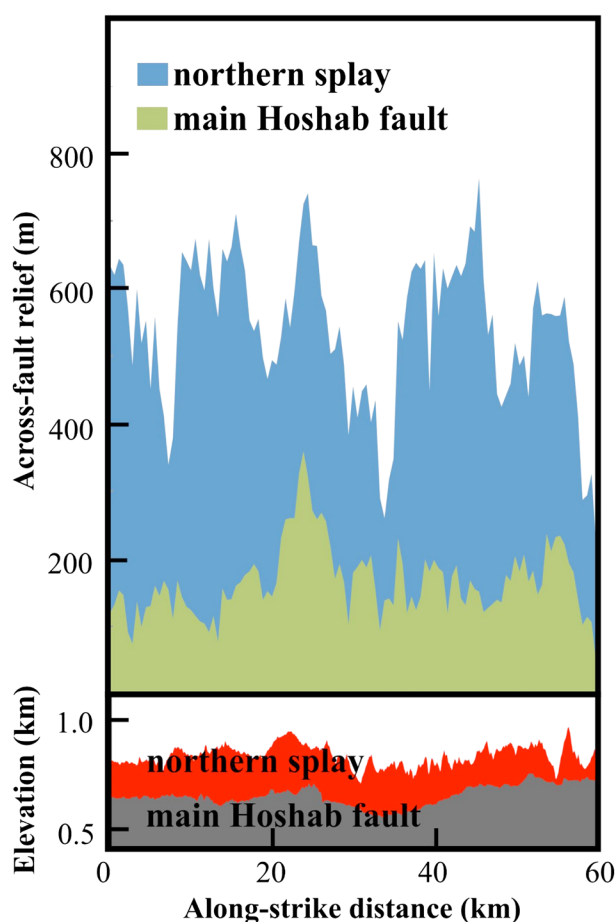


Figure 5. (top) Across fault topographic relief along the southern segment of the Hoshab fault. The topographic relief is defined by the difference between the maximum and minimum elevations along a profile perpendicular to the fault trace from the Shuttle Radar Topography Mission DEM [Farr et al., 2007]. (bottom) The elevation along the main Hoshab fault and its northern splay (as shown in Figure 1).

that separates a bedrock cored range in the north and a Cenozoic sedimentary basin to the south; the preserved lateral offsets on these faults (e.g., 8 m in Figures 4c and 4e and 24 m in Figure 4d) are also of similar magnitude to the surface slip on the Hoshab fault. Therefore, the faults may all behave in a very similar way, together accommodating a large part of the deformation between the Makran and Peninsular India by failure in rare (every few thousand years), large ($M_w \geq 7.5$) earthquakes.

Distributed faulting makes it unlikely that the region south of the Hoshab fault rotates as rigid block about a not-too-distant pole of rotation [Barnhart et al., 2014]. Nonetheless, their combined effect will be to remove material laterally from the region of shortening. We note that the western end of the Hoshab fault rupture makes an angle of about 55° with respect to the shortening direction. Strike-slip motion of ~ 1 cm/yr of the region south of the Hoshab fault relative to north of it [Szeliga et al., 2012] therefore provides a component of motion of ~ 6 mm/yr in the shortening direction (~ 1 cm/yr $\times \cos 55^\circ$). Together with thrusting on the faults similar to that in the 2013 event (~ 2 mm/yr assuming an average shortening of 1.6 m in the 2013 earthquake and an earthquake recurrence interval of 800 years), this could accommodate the total shortening required.

Distributed faulting also provides other possibilities for accommodating the shortening with different faults exhibiting different ratios of strike-slip to dip-slip motion. It has been suggested that the Hoshab fault is segmented and exhibits bimodal slip behavior [Barnhart et al., 2015], with its northern segment exhibiting primarily strike-slip motion, while the southern segment moves mainly as a thrust except when both segments fail and strike-slip motion from the northern segment propagates to the south. It is argued that this hypothesis is supported by the large topographic relief across the southern segment of the Hoshab fault. We find that relief across the southern portion of the Hoshab fault occurs in two steps: part across the main Hoshab fault and a part that is twice as large across the previously unidentified northern splay (Figure 5). Our observations of horizontal to vertical motion on the southern segment of the Hoshab fault suggest it has failed in the same manner in earlier events. However, the overall long-term shortening could be accommodated by standard slip partitioning between the main Hoshab fault and its northern splay. A few old alluvial fans were also identified by Barnhart et al. [2015] as providing evidence for predominant thrust motion on the southern segment of the Hoshab fault. We measured the vertical offset at one of these sites; the 9 m observed (Figure S11 in the supporting information) is only approximately 6 times that of the 2013 vertical offset and can easily be explained by a few earthquakes moving in the same way as the 2013 event.

5. Conclusions

In this study, we use Pleiades stereo imagery to resolve a current controversy of the 2013 M_w 7.7 Balochistan earthquake, in which it has been argued that kinematics of the Hoshab fault switches between strike-slip and dip-slip [Avouac *et al.*, 2014; Zinke *et al.*, 2014; Barnhart *et al.*, 2015]. By determining the vertical component of motion on the fault for the first time, we find the 2013 earthquake in fact exhibits typical behavior for this fault. The cumulative surface displacements from past earthquakes on the Hoshab fault show a constant local ratio of vertical to horizontal slip, suggesting that the Hoshab fault has persisted with the same style of faulting in the late Quaternary. By further mapping of subparallel faults in the eastern Makran, we also show that failure occurs in a distributed fashion and is not constrained solely to the Hoshab fault, providing an explanation for long repeat times and hence a lack of seismic events in previous decades.

Based on the above arguments, we argue that the strike-slip earthquake in 2013 is not a rare event induced by dynamic stresses but is instead a representative event on the Hoshab fault. The curvature of the fault and the rotation of its slip vector may arise from a nonuniform stress field. Although we do not have a detailed strain field for the region, single line-of-sight velocity fields observed by radar interferometry [Fattahi *et al.*, 2014; Lin *et al.*, 2015; Sun, 2015] do display the same curvature as the faults. It is therefore plausible that the principal strain and stress axes also rotate along the length of the faults. The arguments depend on detailed 3-D near-field observations to fully characterize the kinematics of the 2013 Balochistan earthquake. The region of the earthquake provides an example of distributed faulting in a remote and inaccessible area amenable to detailed near-field investigation by the new generation of very high-resolution satellite stereo imagery.

Acknowledgments

The Pleiades DEM is available on request and a kml, of preserved fault scarps and lateral offsets in the eastern Makran region is provided with the online version of this article. Data supporting Figure 3 are available in Table S1 in the supporting information. This work was supported by the University of Oxford through a PAG scholarship to Yu Zhou and the Natural Environment Research Council through the Looking into the Continents from Space large grant (NE/K011006/1) and the Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET). We thank Roger Bilham for providing the GPS velocities. We are grateful to Mike Oskin and an anonymous reviewer for useful comments.

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