The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading

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Detailed studies of earthquakes triggered by a known source of stress change can shed light on the influence of fault frictional properties^{1,2} and preseismic stress^{3,4} on the initiation, propagation and arrest of seismic ruptures. Triggered and induced seismicity can provide unique opportunities to understand this problem⁵⁻⁷. However, direct evidence is rare due to the absence of e.g., near-field surface ground deformation observations^{8,9} and unknown pre-earthquake stress conditions. Here, we collect geodetic data recording the coseismic effects of the Mw 5.1, 11 May 2011 Lorca (SE Spain) moderate earthquake. Elastic modelling results suggest that the nucleation process and main slip area occurred at very shallow depths (2-4 km) on the rupture plane along the Alhama de Murcia fault. Slip extends towards the surface from unstable to stable friction fault segments. We find that the slip area matches well a pattern of positive Coulomb stress change due to groundwater extraction in a nearby basin aquifer. These results indicate that the shallow slip distribution during the earthquake could be controlled by groundwater induced unloading stresses at the upper frictional transition of the seismogenic layer. The relationship between known crustal stress changes (e.g.,

25 **groundwater extraction) and coseismic slip distribution could help, in general, to**
 26 **understand where and how earthquakes tend to occur.**

27 The Eastern Betics Shear Zone in South Spain is a transpressive deformation segment of the
 28 major diffuse Nubia-Eurasia plate boundary (Fig. 1a), where ~NW-SE convergence direction
 29 is accommodated in a complex set of thrusting and strike-slip faults^{10,11}. This region has
 30 suffered a significant number of moderate-to-large earthquakes in the past 500 years and is
 31 considered one of the areas of highest seismic risk in Spain¹². On 11 May 2011 (16:47 UTC),
 32 an earthquake struck the city of Lorca (Fig. 1b), causing significant property damage, injuring
 33 hundreds and resulting in nine fatalities. The epicenter, as determined by the National
 34 Geographical Institute of Spain (IGN), was located ~2 km east-northeast of Lorca, with a
 35 focal mechanism solution indicative of reverse and strike-slip faulting that occurred at very
 36 shallow crustal depths (~3 km)¹². The mainshock has been tentatively attributed to a major
 37 fault in the area, the Alhama de Murcia fault¹² (AMF). Catalogue locations for the entire
 38 sequence (~149 events), present an undistinguished pattern¹²; however detailed seismic
 39 relocation indicates that most events were generated along the AMF¹³ (Fig. 1b).

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41 To constrain the coseismic slip, surface deformation was measured by radar interferometry. In
 42 addition, available GPS data were processed both at daily and at 1-Hz rates to determine static
 43 and transient offsets (see Methods). Two different ENVISAT descending satellite tracks (I2
 44 and I6) imaged the area before and after the event, providing estimates of the displacement
 45 field from two different look angles (Fig. 2a and 2c). Differential interferograms were
 46 processed in time series without temporal filtering (see Methods) and resulting displacement
 47 maps were corrected for a known groundwater subsidence signal¹⁴ (Fig. 1c and 1d, and
 48 Supplementary Information). Coseismic displacement maps show displacements towards the
 49 satellite north of the mapped AMF¹¹, with deformation peaks at ~2.5 cm (Fig. 2a) and ~1.5 cm

(Fig. 2c). Deformation reversed south of the AMF, with ~1 cm of displacement away from the satellite (Fig. 2a and 2c). Finally, deformation in the urban area and south-eastwards with respect to the AMF branch show maximum displacements. All the continuous GPS stations except LORC were stable (Fig. 1a, 2a and 2c). LORC station moved north (4.2 ± 0.8 mm) and slightly to the west (-0.9 ± 0.8 mm), while the vertical motion was not significant. Postseismic deformation can be considered negligible, as evidenced by the absence of transients in the following hours-to-days at LORC (see Supplementary Information).

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We model the ground deformation data using an elastic dislocation model¹⁵. First, we explored for the non-linear dislocation geometry¹⁶, and then solved for the distributed slip. The best-fitting uniform dislocation model indicates a reverse and left-lateral slip fault striking N230E and dipping 70-degrees to NE at very shallow depths (1 ± 0.3 km to 4 ± 0.8 km down dip).

Those parameters indicate that the earthquake rupture occurred along the AMF. Those results are in good agreement with seismically derived focal parameters¹². However, large residuals are found near downtown Lorca (see Supplementary Material). The fault slip distribution was resolved on an extended fault plane (10×10 km²) with a slightly modified strike to match the asymmetric pattern observed in the interferograms (N225E). The preferred smoothed distributed fault slip model allows for two patches of relative maximum slip. A slip area with mainly oblique motion (reverse and left-lateral, ~15 cm) occurs beneath the La Tercia segment-AMF north of the city of Lorca, at depths ranging from 2 to 5 km, which is consistent with an independent fault slip model estimated using a TerraSAR-X differential interferogram¹⁷. A much shallower and smaller slip area with left-lateral to pure reverse motion is found beneath the city along the Lorca segment-AMF, ~5 cm (Fig. 3a). According to the surface geology, the AMF south-eastern branch has been identified as a vertical or

74 south-dipping thrust, from Totana (~15 km northeast) to Lorca^{11,18}. If a small vertical segment
 75 (down to 1 km) is introduced in the fault geometry the data fit is improved (Fig. 2b and 2d).
 76 However, this does not significantly modify the slip pattern (see Supplementary Material).

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78 Crustal (un-)loading due to near-surface masses redistribution (water, ice or quarried material)
 79 can affect the subsurface stress field altering magma production¹⁹ and seismic activity²⁰⁻²². The
 80 Alto Guadalentin basin shows high subsidence rates, >10 cm/yr, due to long-term sustained
 81 groundwater pumping¹⁴ (Fig. 1d). The subsidence area is bounded by nearby faults (e.g.,
 82 AMF) and the Guadalentin river (Fig. 1b), indicative of possible permeability barriers or
 83 structural control in the deposition of compressible sediments. Regional groundwater
 84 depletion and related environmental problems have been recognized since the 1960s²³. While
 85 groundwater table level changes are only available at a few wells, Fig. 1c shows groundwater
 86 depth evolution between ~1960 and 2010, which indicates a drop of at least 250 m. We
 87 investigate whether or not the groundwater extraction activity could significantly affect the
 88 tectonic fault that was activated during the Lorca earthquake, as the unusual shallow slip may
 89 indicate. Here, we calculate the three-dimensional subsurface stress change induced by the
 90 crustal load on a homogeneous elastic half-space using the Boussinesq solution²⁴ and resolve
 91 for the Coulomb stress change (ΔCFF) on the fault geometry. We explored a range of possible
 92 (unknown) groundwater table change areal shapes, aquifer porosities, the role of pore-pressure
 93 diffusion, and fault friction (see Supplementary Information). In Fig. 3b, we present ΔCFF
 94 resolved along the AMF with a slip rake of 36 degrees, in accordance with the published focal
 95 mechanisms. We assume conservative values for the unloading model parameters and a
 96 simple aquifer shape based on the aquifer permeability barriers, as these provide a lower
 97 bound model for the possible stress changes due to the pumping and permanent groundwater
 98 drawdown²³ (see Supplementary Material).

99

100 The actual interseismic slip rate and stress/friction conditions on the fault are unknown, which
 101 precludes their specific inclusion in the stress model. However, before the 2011 earthquake,
 102 the most recent similar, moderate earthquake on the AMF near Lorca occurred in 1818¹².
 103 From paleoseismic estimates for net fault slip (0.07-0.6 mm/yr)¹¹, the accumulated slip deficit
 104 ranges from 1.4 to 12 cm. The upper bound is in good agreement with the estimated
 105 maximum coseismic slip magnitude for this event, indicating that the fault had accumulated
 106 sufficient interseismic tectonic stress to allow for a similar earthquake rupture, assuming that
 107 it had remained fully locked.

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109 Given that the faulting itself was tectonically driven, the pattern of unloading stress changes
 110 due to the anthropogenic groundwater changes coincides to a remarkable degree with the
 111 areas of significant coseismic slip (Fig 3a and 3b). Assuming that the hypocentral location
 112 coincides with rupture nucleation, slip begins north and outwards of the unloaded aquifer area
 113 with a left-lateral to reverse slip component at depths consistent with the maximum values of
 114 ΔCFF (Fig. 3c) for left-lateral to oblique slip motions due to the relative increase of shear
 115 stress change at this region. The ΔCFF model also favours propagation towards the surface
 116 laterally along the fault-bounded aquifer as thrust rupture. All studied models predict an
 117 increase in ΔCFF towards the surface. This propagation pattern also is supported by analysis
 118 of radiated seismic energy directivities^{13,25}, which are consistent with a predominantly SW and
 119 towards-the-surface rupture. However, ΔCFF decreases to smaller values for left-lateral slip
 120 rake beneath the unloading and far from the aquifer border (Fig. 3b), whereas thrust motion
 121 increases due to shallow induced extension (reduction of normal stresses) at depths of 1 km or
 122 less (Fig. 3d). Conversely, the unloading model also explains the slip arrest, as the slip turns
 123 and is dominated by a reverse slip component southwest of the city (Fig. 3a). Slip propagation

ultimately is limited by the earth surface boundary and the low values of pre-stress for encouraging left-lateral ruptures motion along a parallel outward dipping fault at the same location (Fig. 3). The arrest of the coseismic slip propagation in this location also coincides with the intense shaking and damage in the southwestern part of Lorca (Barrio de La Viña).

Based on established studies of fault mechanics²⁶, depth-dependent fault frictional change and reduced stresses close to the surface prevent surface coseismic slip²⁵. These limit the maximum slip area during seismic rupture, inferred from geodetic and seismic data to occur at middle crustal depths of 3-8 km⁵. The inferred slip depth here may indicate that the rupture nucleated at the transition zone between velocity-weakening and velocity-strengthening zones (Fig. 3c). The fault slip propagation towards the surface and into the velocity-strengthening area would require that anomalously high-dynamic stresses develop at the crack tip and/or a thick fault gouge²⁶. Although the shallow slip area could be an early afterslip effect, it would be limited to the first fifteen days following the earthquake, in accordance with the radar data (Fig. 2a and 2c). Again, LORC GPS station shows no evidence of postseismic motion. We favour shallow coseismic slip based on the interpretation that the high stress conditions required to propagate coseismic slip into the shallow velocity-strengthening volume likely were in place before the event, as a consequence of the cumulative long-term unloading stress change and the relative position of the fault with respect to the depleted aquifer (mainly shallow extension parallel to the unloading source and left-lateral shear at the aquifer edge boundary). It has been shown that three-dimensional crustal (un-)loading processes can promote long-term fault slip or modulate seismicity beneath the (un-)loading source^{20,27,28} and on the periphery^{22,29}. Here we present observations and modelling results for a possible link between the crustal unloading and the slip pattern during a single earthquake.

149 We conclude that the presented data and modelling results are consistent with a groundwater
150 crustal unloading process, providing a reasonable explanation for the observed fault slip
151 pattern, as well the propagation and arrest of fault slip during the earthquake into the shallow
152 crustal velocity-strengthening fault zone. This study reveals an unexpected human-induced
153 alteration of the ambient subsurface stress field close to an active seismogenic source, and
154 provides insights into processes that could modify the seismic hazard analysis and elsewhere.

155

Methods

We correct the differential interferograms for orbital trends by adjusting a bilinear function in a least squares sense. We estimated the bilinear model using the entire interferogram. Masking the deformation area has a negligible effect. We estimated for the displacement time series and associated errors using a multitemporal InSAR time series method (see Supplementary Material). It takes into account decorrelation, individual atmospheric noise, and observations redundancy from a Monte Carlo estimation process³⁰. Interferogram atmospheric noise was estimated fitting a 1D zero-order Bessel and exponential covariance function based on randomly distributed points, but excluding points in the deformation region. The final displacement maps were obtained by differencing the time series, and errors for each coherent pixel ($\rho > 0.2$) in the displacement map were obtained by error propagation of estimated formal errors for each considered time series step.

GPS data were analyzed using all continuous stations in SE Spain spanning the 2006.00-2011.67 period. The processing of GPS data was done using two different strategies. All data sets were processed on a daily basis by using the GAMIT-GLOBK software packages to characterize the long-term and coseismic deformation patterns (Fig. 1). A 3 day period of high-rate data (1-Hz sampling) was processed by applying the instantaneous GPS positioning method to detect transient deformation associated to the earthquake occurrence (see Supplementary Material).

In the unloading mechanical model, we assumed 50 years (~1960-2010) of cumulative ΔCFF (slip-rake=36) resolved on the rupture fault-plane by crustal unloading due to 5 m/yr of groundwater table drop in an aquifer with 5% effective porosity. We approximate the aquifer shape as a rectangular unloading source shape (10x8 km² area, shown in Fig. S11a). The vertex of the aquifer is coincident with the point where the mapped fault trace changes in strike (La Tercia and Lorca segments of AMF), north of Lorca. At this location, the aquifer and mapped groundwater induced subsidence area are limited by the Guadalentin river, which runs approximately perpendicular to the Lorca-AMF segment (Fig. 1b and S11a). We assumed values for fault friction, $c=0.5$, and Skempton coefficient, $B=0.6$. Other models were also tested (see Supplementary Material). Files containing the displacement maps, fault-slip distribution model, and location of point sources for loading modelling can be obtained upon request to the corresponding author.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

The file contains Supplementary Text, Supplementary Tables S1-S2, Supplementary Figures S1-S13 with legends, and Supplementary References.

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Authors' contributions

PJG carried out the radar data analysis; dislocation, loading and pore-pressure diffusion models, and wrote the manuscript with the help of all co-authors. KFT and PJG carried out the CFF models. MP processed daily GPS data and computed the 2D strain-rate tensor. FC processed high-rate GPS data and analysed accelerometers frequency spectrum. JF and PJG designed the research.

Author information

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Figure 1 | Location and kinematics of the Lorca earthquake. **a** SE Spain seismicity (2000-2010), focal mechanisms (1970-2010), long-term GPS velocity (2006-2011, gray), and coseismic vectors (red). Major mapped faults are labelled. **b** Lorca city and Alto Guadalentin basin. IGN mainshock focal mechanisms (black), pre-shock (light-gray) and largest aftershock (dark-gray), and relocated seismic sequence¹³. Black stars are damages locations; Red lines faults¹¹. Contour lines indicate 2 cm/yr InSAR subsidence due to groundwater pumping¹⁴. Blue rectangle: fault surface projection. **c** Groundwater depth evolution from different data sources (see Supplementary Information). **d** InSAR (triangles) and LOS projected GPS ground surface subsidence at LORC station.

Figure 2 | Ground deformation data and model. Descending LOS displacement maps and LORC station horizontal GPS vector (**a** and **c**) and distributed slip model predictions (**b** and **d**). **a** and **b** Data and model for track 008 (20110426-20110526). **c** and **d** Data and model for track 209 (20110510-20110609). Insets in **a** and **c** indicate LOS angle, positive values away from satellite. Blue rectangle: fault surface projection. Dashed lines are profile locations (**a-d**). **e** and **f** Observed and simulated data along two profiles, and local topography. 2σ data profiles based on standard deviation in a 1-km wide area normal to the profile direction.

Figure 3 | Fault slip and unloading stress change models. **a** Coseismic distributed fault slip model. **b** 50-years (~1960-2010) of cumulative Δ CFF (slip-rake=36) resolved on the rupture fault-plane by crustal unloading. **c** and **d** show fault-dip profiles ~2.5 km north of city (**c**) and in the Lorca (**d**) for the coseismic slip, and three cumulative unloading Δ CFF models with variable slip-rake (thrusting=blue, left-lateral=green and oblique=red with rake=36°). Background **c** shows depth percentage of the long-term crustal seismicity (2000-2010) located

301 [www.ign.es] in SE Spain, under similar compressive regime, used to infer the depth of the
302 upper frictional transition limit.
303