Slow slip events and megathrust coupling changes reveal the earthquake potential before the 2020 Mw 7.4 Huatulco, Mexico, event

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ABSTRACT

Stress accumulation on the plate interface of subduction zones is a key parameter that controls the location, timing and rupture characteristics of earthquakes. The diversity of slip processes occurring in the megathrust indicates that stress is highly variable in space and time. Based on GPS and InSAR data, we study in depth the evolution of the interplate slip-rate along the Oaxaca subduction zone, Mexico, from December 2016 through August 2020, with particular emphasis on the pre-seismic, coseismic and post-seismic phases associated with the June 23, 2020 Mw 7.4 Huatulco earthquake to understand how different slip processes contribute to the stress accumulation in the region. Unlike two time-invariant interplate coupling models previously proposed for the region, our results show that continuous changes in both the stress-releasing aseismic slip and the coupling produced a high stress concentration (i.e. Coulomb Failure Stress (CFS) of 700 ± 100 kPa) over the main asperity of the Huatulco earthquake and a stress shadow zone in the adjacent updip region (i.e. shallower than 17 km depth with CFS around -500 kPa). These findings may explain both the downdip rupture propagation (between 17 and 30 km depth) and its impediment to shallower, tsunamigenic interface regions, respectively. Interplate coupling time variations in the 2020 Huatulco and the nearby 1978 (Mw 7.8) Puerto Escondido rupture zones clearly correlate with the occurrence of the last three Slow Slip Events (SSEs) in Oaxaca far downdip of both zones, suggesting that SSEs are systematically accompanied by interplate coupling counterparts in the seismogenic zone that in turn have their own potentially-seismogenic stress and frictional implications. In the same period, the interface region of the 1978 event experienced a remarkably high CFS built-up of 1,000-1,700 kPa, half imparted by the co-seismic and early post-seismic slip of the neighboring Huatulco rupture, indicating large earthquake potential near Puerto Escondido. Continuous monitoring of the interplate slip-rate thus provides a better estimation of the stress accumulation in the seismogenic regions than those given by time-invariant coupling models and

improves our understanding of the megathrust mechanics where future earthquakes are likely to occur.

MAIN TEXT

1. Introduction

Large earthquakes occur along subduction zones in regions known as asperities (Lay and Kanamori, 1981), which represent locked areas of the interplate contact where frictional resistance allows elastic stress to build up during tens to hundreds of years as a consequence of the relative plate motion. Under the simple concept of Coulomb failure criterion, an earthquake occurs when the shear stress overcomes the strength of the fault. Both stressing-rate and fault strength are parameters that vary in time and space during the megathrust earthquake cycle (Moreno et al., 2011). Therefore, understanding the tectonic processes that cause these variations is essential to assess the seismic hazard in subduction zones.

Inter-seismic coupling maps obtained from geodetic observations have been widely used to identify heterogenous, highly locked segments of the plate interface where large earthquakes take place (Chlieh et al., 2008; Loveless and Meade, 2011; Moreno et al., 2010; Perfettini et al., 2010). Most of these estimations consider a steady-state long term deformation during the inter-seismic periods that results in a time invariant locking pattern. However, it has been observed that interplate coupling also varies with time (Heki and Mitsui, 2013; Melnick et al., 2017) and might be caused by different processes such as pore pressure transients (Cruz-Atienza et al., 2018; Materna et al., 2019; Warren-Smith et al., 2019) or dynamic stresses from regional earthquakes (Cruz-Atienza et al., 2020; Delorey et al., 2015; Materna et al., 2019).

During the inter-seismic period, a broad spectrum of tectonic processes occurs on the plate interface with distinctive spatiotemporal characteristics that play an important role to accommodate the strain along the megathrust. Among these processes, short-term and long-term slow slip events (SSEs), which are aseismic slip transients lasting from days to months, release the strain accumulation in the deeper and shallower segments of the plate interface (Beroza and Ide, 2011; Saffer and Wallace, 2015). Since their discovery, observations and theoretical models have proposed that SSEs increase the stress in the adjacent seismogenic zone and may trigger damaging earthquakes (Obara and Kato, 2016; Segall and Bradley, 2012; Uchida et al., 2016; Voss et al., 2018). Moreover, it has been documented that major interplate earthquakes in different subduction zones are preceded by SSEs, although the actual mechanisms of their interaction remain under debate.

In the Mexican subduction zone, the recurrence of Mw 7+ interplate earthquakes is ~30–50 years (Singh et al., 1981). In the deeper segment of the megathrust (30-50 km depth), long-term SSEs occur in Oaxaca and Guerrero with recurrence of 1.5 and 3.5 years, respectively (Cotte et al., 2009; Graham et al., 2016). The last four Mw 7+ interplate events in the Mexican subduction zone were preceded by SSEs in the downdip adjacent region: The 2014 Mw 7.4 Papanoa earthquake in Guerrero (Radiguet et al., 2016) and three more in Oaxaca, the 2012 Mw. 7.5 Ometepec earthquake (Graham et al., 2014a), the 2018 Mw 7.2 Pinotepa earthquake (Cruz-Atienza et al., 2020) and, as it will be shown later, the 2020 Mw 7.4 Huatulco earthquake. These observations suggest that the prevalent mechanism of the interaction between SSEs and unstable shallower regions in the Mexican subduction zone is the stress loading from adjacent slow slip processes. Although SSEs do not always trigger large earthquakes, they do interact periodically with the updip locked regions, thus contributing with the total stress built-up of the seismogenic zone.

Three years before the 2020 Huatulco earthquake, a complex sequence of SSEs and devastating earthquakes took place from June 2017 to July 2019 in central and southern Mexico, including the Mw 8.2 Tehuantepec and Mw 7.1 Puebla-Morelos earthquakes in 2017, and the Mw 7.2 Pinotepa earthquake in 2018, describing a cascade of events interacting with each other on a regional scale via quasi-static and/or dynamic perturbations (Cruz-Atienza et al., 2020). In Oaxaca, the plate interface slipped (aseismically) almost continuously for the whole two years period with at least two reactivations, one during the post-seismic relaxation of the Mw 7.2 Pinotepa earthquake, and the second one with the 2019 Oaxaca SSE.

Here we thoroughly study the evolution of the interplate slip-rate history in the Oaxaca segment during this unprecedented sequence including the pre-seismic, coseismic and post-seismic phases of the 2020 Huatulco earthquake with the aim of understanding how these processes contribute to the seismic potential in the region. We show that the continuous and simultaneous monitoring of SSEs and the megathrust coupling provides a better estimation of the stress accumulation on the locked regions where future large earthquakes are expected to occur.

2. The 2020 Mw 7.4 Huatulco Earthquake

2.1 Coseismic slip inversion

On June 23, 2020, a shallow Mw 7.4 interplate thrust earthquake took place below the state of Oaxaca, Mexico (Fig. 1), with relocated hypocentral coordinates (15.822º, -96.125º, 17.2 km, determined from seismic records at the station HUAT of the Mexican Servicio Sismológico Nacional (SSN), which is 7 km south of the epicenter) within the aftershock area of the 1965 Mw 7.5 earthquake, the last interplate rupture in this region (Chael and Stewart, 1982).

We combined nearfield GPS and Interferometric Synthetic Aperture Radar (InSAR) data to obtain the coseismic slip distribution by means of ELADIN, a newly developed adjoint inversion method (Tago et al., 2020) (see Supplementary Materials). For the GPS data we used high rate (1 s) time series to measure the coseismic static displacement at four stations near the epicenter (Figs. 1c and S1c-f). The displacement in Huatulco (HUAT station), the closest epicentral site, was carefully and independently estimated using GPS, tide gauge and strong motion data, yielding very consistent values of 49 cm uplift and 40 cm seaward displacement (Figs. S1b and S1c). The InSAR line-of-sight (LOS) displacement map (Figs. 1b and S2) was generated from scenes taken before the earthquake, on June 19, and two days after the earthquake, on June 25, by the Sentinel satellite of the European Space Agency on ascending track 107. The InSAR data processing is described in the Supplementary Materials. For all slip inversions presented in this work we assumed the 3D plate interface geometry introduced by Cruz-Atienza et al. (2020) and discretized it, for the coseismic solutions, into subfaults with planar square projections of 5 x 5 km^2.

To determine the optimal data weights for the joint inversion of GPS and InSAR data we first inverted each data set independently. Both solution models produced almost a perfect data fit (Figs. S3a and S3b). The solution using only GPS data describes a very simple and concentrated slip patch downdip the hypocenter with a maximum value of 4.2 m and a marginally lower than expected moment magnitude Mw 7.32 with average GPS data error of 0.2 ± 0.2 cm (Fig. S3a). The resulting model using only InSAR data describes a more heterogeneous slip distribution with maximum value of 2.5 m and a slightly higher moment magnitude of 7.34 with average InSAR data error of 0.0 ± 1.2 cm (Fig. S3b). Different joint inversion tests led us to optimal data weights (see Supplementary Materials) producing a final solution that satisfactorily explains both sets of observations with average GPS and InSAR data errors of 1.2 ± 1.0 cm and 0.2 ± 2.1cm, respectively (Figs. 1 and S3c).

Fig. 1a features our preferred coseismic slip solution with two main patches, the most prominent downdip the hypocenter, between 21 and 32 km depth with peak value of 3.4 m, and a second one 45 km east-northeast, almost below the coast (peak value of 1.8 m), which differs from a recently published solution (Melgar et al., 2020) that did not integrate the closest (GPS and strong motion) data and estimated a static uplift in Huatulco 6 cm higher than ours. Our slip solution explains both the uplift and seaward displacement there, and shows that no significant slip (i.e. larger than 1 m) took place offshore (Fig. S3c). Furthermore, it clearly suggests a rupture directivity towards the north-northeast, essentially downdip from the hypocenter. Two more features stand out from our model: 1) The rupture ends abruptly updip and very close to the nucleation point. 2) The downdip slip limit might correspond to the end of the locked segment of the megathrust, as observed for the 2018 Pinotepa Earthquake (Li et al., 2020) and the aftershocks areas of regional interplate earthquakes (white patches in Fig. 1).

Whether the 2020 Huatulco earthquake is a repetition of two previous events that occurred in 1928 (Ms 7.6) and 1965 (Ms 7.4) is an important matter that goes beyond the scope of this work. However, since this question can be addressed by comparing far-field waveforms of the earthquakes, which are sensitive to the source depth (Chael and Stewart, 1982; Singh et al., 1984), we performed a supplementary inversion exercise where the interface was shifted 3.5 km upward to match our relocated hypocentral depth. The inversion yielded similar source characteristics as described above (Fig. S4) with some differences discussed in the Supplementary Materials that do not have a significant bearing on any subsequent analysis.

2.2 The 2020 Oaxaca SSE that preceded the earthquake

Two months before the Huatulco earthquake, on mid-April 2020, three GPS stations in Oaxaca (TNNP, TNNX and OAXA) changed their typical interseismic motion from roughly northeast to southwest, indicating a transient deformation associated with a SSE (light blue section in Figs. 2a and S6a). We used continuous displacement records on 12 permanent GPS stations in Oaxaca belonging to the SSN and Tlalocnet (Cabral-Cano et al., 2018), between September 2019 and the Huatulco earthquake date (Fig. S5) to simultaneously invert for the plate interface coupling (PIC) and any stress-releasing slip episode (e.g. SSEs) in successive time windows using ELADIN (Fig. 2). For these and the next inversions, the 3D plate interface was discretized with coarser subfaults of 10 x 10 km^2.

Fig. 2e shows the main slow slip patch downdip of the 1978 Puerto Escondido earthquake region, between 25 and 50 km depth, with an equivalent moment magnitude Mw 6.4 (Mo = 7.914×10^{18} N*m assuming a shear modulus of 32 GPa). The location and magnitude of this SSE are consistent with previously reported SSEs in Oaxaca (Correa-Mora et al., 2008; Cruz-Atienza et al., 2020; Graham et al., 2016). It is also clear that the SSE did not penetrate the rupture area of the Huatulco earthquake. Instead, we observe a remarkable PIC evolution previous to the event in that area, where the interface decoupled around February-March (Fig. 2d) before getting fully coupled just before the earthquake (i.e. during the strongest SSE phase, Fig. 2e). This can also be seen directly in the GPS time series at the stations closest to the epicenter, such as OXUM and HUAT (Fig. 2a), where we do not observe the SSE southward rebound before the earthquake. In contrast, the displacement trends present a slight acceleration to the north. Something similar occurred in the hypocentral region of the 2018 Pinotepa earthquake 200 km west, where the seismicity rate also increased in the two months preceding the rupture (Cruz-Atienza et al., 2020). We carefully analyzed the foreshock seismicity starting from August 2016 in the hypocentral region of the Huatulco earthquake using the one-station template-matching procedure introduced by Cruz-Atienza et al. (2020) using continuous broadband records at the HUIG station (Fig. S7). However, unlike the observations of the 2018 Pinotepa earthquake, we did not find significant increase in the seismicity rate before the event that could shed light on the rupture initiation mechanism.

Although the transient deformation produced by the SSE is noticeable from mid-April, the inter-SSE displacement trends in some stations started changing well before, around mid-February as observed in Fig. 2a, suggesting a gradual plate-interface decoupling process at a regional scale preceding the SSE-induced crustal relaxation, which can be observed in Figs. 2b-2d (and Supplementary Movie S1). Before this process began (Fig. 2b), the downdip segment of the plate interface, between 25-50 km, was fully coupled while small SSE episodes were taking place in both the 2018 Pinotepa earthquake area and up-dip of the Huatulco earthquake rupture zone. In the following two months, there seems to have been an incipient downdip SSE propagation from south to north in Pinotepa along with another small relaxation to the east of the area where the long-term SSE will develop (Supplementary Movie S1 and Figs. 2b-2c). Then, in Fig. 2d we see how the segment downdip of the 1978 earthquake area is the last one to experience a PIC reduction (i.e. the interface slip starts accelerating but always below the plate convergence rate) leading to the main SSE patch occurrence in April-June, the months preceding the earthquake (Fig. 2e). All of these observations clearly demonstrate the regional-wide preparatory phase for the 2020 Oaxaca SSE.

A common practice to isolate the deformation associated with slow slip transients is to subtract the inter-SSE linear trend from the GPS time series. The residual deformation is then assumed to correspond to the strain released by the SSE (e.g., (Bartlow et al., 2011; Hirose et al., 2014; Radiguet et al., 2011)). When one does this to invert for the slip at the interface, the preparatory phase of the SSE (i.e. the slow decoupling process preceding the SSE relaxation) is mapped/interpreted as aseismic slip resulting in an elastic crustal rebound (i.e. a stress drop), which is not really correct. This assumption leads to systematic overestimations of the SSE related displacements and thus the equivalent seismic moment with relevant implications in the scaling properties of slow earthquakes and, more importantly, in the slip budget over several SSE cycles, which may be significantly underestimated.

2.3 Early post-seismic deformation

We inverted the early post-seismic GPS displacements (i.e. the first 2 months discretized in 6 ten-day windows, Figs. 3a and S6b) produced by the mainshock using the same parameterization for the ELADIN method as in the previous section. We then assumed that such displacements are only due to the afterslip on the plate interface, which is a reasonable approximation considering that the viscoelastic relaxation after a similar thrust event 260 km west, the 2012 (Mw 7.5) Ometepec earthquake, was negligible in a post-seismic period three times longer (Graham et al., 2014b).

Four main observations arise from the afterslip evolution of the Huatulco earthquake (Fig. 3b and Supplementary Movie S1): (1) the largest afterslip concentrates between 20 and 50 km depth involving also the main SSE patch occurred before the earthquake (i.e. downdip from the 1978 rupture area) and where previous SSEs have been identified (Fig. S8); (2) the maximum postslip area completely overlaps with the coseismic rupture area; (3) the afterslip spreads offshore up to the oceanic trench where most of aftershocks were concentrated; and (4) the afterslip rate reaches its maximum value of 390 cm/year during the first 10 days following the event.

The complete overlap of coseismic and postseismic slip has been observed in the last three interplate thrust earthquakes (Mw > 7) in Oaxaca, the 2012 (Mw 7.5) Ometepec (Graham et al., 2014b); the 2018 (Mw 7.2) Pinotepa (Cruz-Atienza et al., 2020) and the 2020 (Mw 7.4) Huatulco (this study) events, indicating that these seismogenic segments of the plate interface, with the depth range between 10 and 30 km, can release elastic strain energy both seismically and aseismically. The peak afterslip velocity of the Huatulco event reported above is almost seven times higher than the one of the Pinotepa earthquake (Supplementary Movie S2) (Cruz-Atienza et al., 2020), suggesting significant lateral differences in the mechanical properties along the Oaxaca subduction zone.

The cumulative aseismic moment released during the first two months following the earthquake was 1.808×10^{20} N*m, equivalent to a moment magnitude Mw 7.44, which is 24% larger than the coseismic moment. The high postseismic/coseismic moment ratio is also a common feature of the three Oaxaca events mentioned above, that significantly differs from the much lower estimate for the 2014 (Mw 7.4) Papanoa thrust earthquake in Guerrero, where the aseismic postslip moment was 30% smaller than the corresponding coseismic value (Gualandi et al., 2017).

One of the most noteworthy features of the postseismic process in the region is that the Huatulco earthquake postslip did not penetrate the rupture area of the 1978 Puerto Escondido earthquake (dashed ellipse in Fig. 3b), which remained fully coupled during the two-month period. Unlike the preseismic phase, the PIC in the 1978 rupture area abruptly increased just after the earthquake (compare Figs. 2 and 3) suggesting significant dynamic implications in terms of the postseismic strain accommodation in the region.

3. Interplate slip-rate evolution in the Oaxaca subduction zone.

Before the occurrence of the Huatulco earthquake, a complex sequence of earthquakes and SSEs took place in an unusual way along the Mexican subduction zone from April 2017 to September 2019 (Cruz-Atienza et al., 2020). During the sequence, the plate interface experienced remarkable changes of the PIC in the whole megathrust over time (see Supplementary Movies S1 and S2). Fig. 4 summarizes two examples of these remarkably changes where high coupled regions (PIC > 0.6) evolve before (green patches) and after (warm color patches) the Pinotepa and Huatulco earthquakes.

We analyze the evolution of the aseismic slip along the Oaxaca megathrust before the Huatulco earthquake by using the slip history inverted by Cruz-Atienza et al. (2020) (from December 2016 to September 2019) and the sequence inverted before the Huatulco earthquake (Fig. 2), linearly interpolated every 30 days. Fig. 5a shows the evolution of the total aseismic slip on the plate interface along the trench (i.e. projected into the green lines of Fig. 4) averaged between 10-30 km depth, which include the segments of the 2018 Pinotepa, 1978 Puerto Escondido and 2020 Huatulco earthquakes (Fig. 4). Thus, the difference between the final cumulative slip curve and the dashed line, which represents the expected total displacement of the incoming Cocos plate during the same period (DeMets et al., 2010), can be interpreted as the slip deficit along the trench in this particular period.

We disaggregated the plate interface aseismic total slip into the slip transients associated with SSE and afterslip, i.e., those events that release elastic strain (Fig. 5b), and the slip that occurs under the coupling regime, i.e., the interplate creep that produces stress build-up and where the slip velocity is less than or equal to the plate convergence rate (Fig. 5c). For a given time window, we distinguish whether a subfault is creeping (in coupling regime) or if it is aseismically slipping releasing stress. Fig. 5b shows that the afterslip contribution from the Pinotepa earthquake dominates in the region, although there were SSEs in this segment before the earthquake (blue to green areas below the red curve). There is also a portion of the Huatulco segment where some small SSEs contribute to the total slip in the plate interface, while this contribution is negligible in the 1978 rupture area.

The evolution of creeping (Fig. 5c) reveals strong variations of the slip velocity in different time intervals along the whole Oaxaca segment, i.e. the interplate coupling significantly changes over time. Some of the most prominent changes of the PIC occur before and after SSEs (e.g. black rectangles), as well as in the 1978 earthquake region during the post-seismic deformation of both the Pinotepa and Huatulco earthquakes, as previously discussed in Figs. 2, 3 and 4.

To better analyze the interplate slip-rate variations we extracted the time series of the slip evolution at four places of the plate interface (dashed circles with radius of 20 km in Fig. 4). Region A, over the rupture area of the Huatulco earthquake; Region B, over the rupture area of the 1978 Puerto Escondido earthquake estimated by Mikumo et al. (2002); Region C, updip from the Huatulco earthquake where most of its aftershocks are located; and Region D, downdip from the rupture area of the Puerto Escondido earthquake. Figs. 6 and S9a show the evolution of the mean total aseismic slip (black line), the creeping (yellow line), the relaxing slip (red line) and the PIC (blue line) within each of the four circular regions.

In the Huatulco rupture area (Region A, Fig. 6a), the contribution to the total slip is mainly due to creeping except for a period after the Mw 8.2 Tehuantepec earthquake, when aseismic stress release occurred on this patch. This 2017 SSE was indeed triggered by the quasistatic and dynamic stresses produced by the great Tehuantepec event as demonstrated by (Cruz-Atienza et al., 2020). In this region, PIC is highly variable over time and correlates remarkably well with the occurrence of neighboring SSEs in Oaxaca even though these events did not penetrate the region. During the occurrence of such regional SSEs, the PIC gradually decreases down to values of 0.2-0.4 and then increases in the final stage of the SSEs to recover the relatively high values of 0.7-0.9 observed in the inter-SSE periods. This behavior is very similar in Region D (Fig. S9a), downdip from the 1978 rupture area, except that PIC starts to recover after the end of the 2019 SSE.

In the 1978 rupture area (Region B, Fig. 6b) there is no evidence of aseismic stress release, so the total slip is only associated with creeping. Although it is not so clear as in Region A, this case is also characterized by large variations of the PIC that correlate with the occurrence of regional SSEs and postslip. There is for instance a great variation of the creeping rate before and after the Pinotepa earthquake, where the PIC raises from ~0.3 before the earthquake (i.e. during the final stage of the 2017 Oaxaca SSE) to almost 1.0 (fully coupled) just after the earthquake, and then gradually decreases to a low PIC value during the corresponding postseismic relaxation. Also notice the sharp growth of PIC in both regions A and B during the 2020 Oaxaca SSE just before the Huatulco earthquake.

Offshore (and updip) from the Huatulco earthquake (Region C, Fig. 6c) we find a more consistent low PIC value across the whole studied period with some exceptions after the Tehuantepec earthquake and just before the initiation of the 2020 SSE. The gap in the PIC curve between December 2018 and the end of March 2019 means that all subfaults within this region underwent a SSE. The red curve indicates that there are small and persistent SSEs in this offshore region over time, which is consistent with the significant afterslip developed there after the Huatulco earthquake that extended up to the trench. These observations suggest that the frictional properties of this region are prone to release aseismically a fraction of the accumulated stress.

4. Implications of SSEs and PIC changes on the stress built-up

Variations in the interplate aseismic slip rate have important implications for both friction (Im et al., 2020) and the stress build-up along the megathrust. We estimated the Coulomb Failure Stress (CFS) changes (Nikkhoo and Walter (2015), see Supplementary Materials) produced by the relaxing slip (SSEs and afterslip) and the interplate coupling to elucidate how the stress evolves along the Oaxaca segment. For this analysis we have also included the coseismic stresses imparted by the Pinotepa and Huatulco earthquakes. Figs. 7a and 7b show the average cumulative CFS every 30 days from December 2017 up to the moment of the Huatulco event along the trench for two different depth ranges encompassing the rupture areas of the 2020 Huatulco (between 20 and 30 km depth) and the 1978 Puerto Escondido (between 10 and 20 km depth) earthquakes. It is important to note that these estimates of the CFS are the result of stress contributions from the whole plate interface and not just from the sub-faults delimited by the depth bands.

As expected, the CFS cumulative rate is highly variable over time and along the trench. For the deeper band (Fig. 7a), we observe that despite the great variations of the slip-rate on the megathrust, the CFS in Huatulco always increased up to values ranging from 400 to 800 kPa. The same happens downdip of the 1978 rupture, where the cumulative CFS is even higher (between 800 kPa and 1 MPa). For the shallower band (Fig. 7b), the CFS decreases and remains negative right updip of the Huatulco rupture reaching values of ~-500 kPa. Such negative values are associated with the stress shadows produced by neighboring strong coupled segments (e.g. the 1978 earthquake area, Fig. 7c) and the periodic release of stress by short-term SSEs in this eastern segment (Figs. 2 and 7d). To the west, in the 1978 rupture area, we find the opposite situation. The CFS always increased to values between 200 and 500 kPa, which are approximately half of the CFS estimates downdip of this segment (Fig. 7a).

Fig. S10 shows both the long-term and inter-SSE time-invariant interplate coupling models estimated by Radiguet et al. (2016) together with their associated CFS change rate. Both models produce large stressing rates mainly in the highly coupled segment of the 1978 earthquake region. However, they also produce large stress shadows in the adjacent less coupled regions (both along-dip and along-strike) such as in the Pinotepa and Huatulco rupture zones. In contrast, our aseismic time-evolving slip-rate model predicts a very different scenario. Fig. 8a shows the cumulative CFS at the time of the Huatulco earthquake including contributions of all aseismic slip processes imaged in the megathrust during the 3.5 years preceding the event (from December 2016 to June 23, 2020). A simple inspection reveals large differences in the stress build-up pattern with respect to the time-invariant models, especially in both the Huatulco and Pinotepa rupture areas, and east-southeast of the 1978 earthquake zone. The bottom four panels of Fig. 8 show the cumulative (trench-perpendicular average) CFS along the trench for the same two bands with different depth ranges analyzed earlier. The left column shows the cumulative CFS at the time of the Huatulco earthquake, while the right column shows the same quantity plus the coseismic and postseismic stress increments.

In the deeper band at the moment and within the rupture area of the Huatulco earthquake (Fig. 8b), the CFS from our time-evolving slip model (blue area) indicates almost double the CFS predicted by the inter-SSE coupling model (yellow area) and more than twice in the downdip region of the 1978 rupture area. On the contrary, the long-term coupling model (orange area) predicts negative CFS values in Huatulco (i.e. no earthquake potential) and low positive values in the downdip region of the 1978 rupture. When adding the CFS imparted by the Huatulco earthquake and its postseismic afterslip (Fig. 8e), our estimate doubles up right downdip of the 1978 rupture area, from about 800 kPa to over 1.8 MPa. A significant fraction of this value is due to the persistently high coupling in this region throughout the post-seismic phase (Fig. 3). This large segment west of the Huatulco rupture (Region D in Fig. 8d) is then very prone to a future earthquake, as has occurred in neighboring regions over the deep part of the locked zone, where the last two interplate earthquakes in Oaxaca (the Pinotepa and Huatulco events) took place with most of their seismic moment released below 20 km (Li et al., 2020).

In the shallower band, the three models predict similar CFS values over the 1978 rupture area before the Huatulco rupture (Fig. 8c), although the inter-SSE model gives much higher values in the eastern part of the main patch. Between the 1978 and Huatulco ruptures areas, only our short-term model predicts a CFS deficit, which is fully compensated (reaching positive values around 800 kPa) by the coseismic and postseismic deformations produced by the Huatulco earthquake (Fig. 8f).

We can therefore distinguish three major differences between our time-evolving CFS estimates, which integrate all contributions from relaxing slip (SSEs and afterslip) and coupled regions in Oaxaca, and both time-invariant coupling models: (1) very high stress concentration over the rupture area of the Huatulco earthquake predicted only by our model, (2) absolute CFS values between 20 and 30 km depth at least twice as high in our model, and (3) a large stress shadow zone updip the Huatulco rupture that is absent in both time-invariant models.

We now analyze in depth the CFS stress evolution in the Huatulco and 1978 rupture areas (within the circular regions A and B, Fig. 8a) given by our time-evolving interplate slip-rate model. Figs 9a and 9b show the total CFS evolution in both regions (black curves) together with the linear predictions given by the time-invariant coupling models of (Radiguet et al., 2016) (green lines). To assess which slip process dominates the stress build-up, we also disaggregated the total CFS into the stress contributions produced by regions in coupling regime only (yellow curves) and by the relaxing slip only (red curves).

In the Huatulco rupture zone (Region A, Fig. 9a) our model shows a sustained growth of the total CFS during the 3.5 years prior to the rupture, reaching values close to 700 kPa and where 80% of the stress contribution comes from interface regions in coupling regime. The remaining 20% is mainly associated with the contribution of the SSE occurred following the 2017 Tehuantepec earthquake. In contrast, the time-invariant long-term coupling model predicts a sustained decrease of CFS that implies a continuous reduction of the earthquake potential. On the other hand, while the inter-SSE time-invariant model predicts a growth of the CFS, the final value is about one third of what our model yields. Since the Huatulco earthquake took place, it seems that our time-evolving slip-rate model and its associated CFS clearly represents a more realistic description of the actual megathrust processes than any of the time-invariant coupling models analyzed here. This is also easily seen by comparing our CFS estimates in the hypocentral region at the time of the earthquake (Supplementary Movie S1 and Fig. 8a) with those produced by the time-invariant coupling models (Fig. S10).

Considering the 1978 Puerto Escondido rupture zone (Region B, Fig. 9b), although our model predicts an effective CFS increase of about 400 kPa at the time of the Huatulco earthquake, it also reveals significant temporal variations that are primarily controlled by the stress contributions from interface regions in a coupling regime. At that time, the stress produced by SSEs is 100 kPa, which represents ~25% of the total CFS. For this specific region, while the inter-SSE time-invariant model predicts a cumulative stress that is almost twice our model's prediction, the long-term time-invariant model is close to our time-evolving cumulative value. When integrating the stress contributions from both the coseismic and postseismic slip of the Huatulco earthquake, then our stress estimate gets close to the inter-SSE prediction with high CFS values around 800 kPa.

Fig. S11 presents the contributions to the CFS of both relaxing slip and coupling separately. Although in very different proportions, both contributions promote an increase in earthquake potential in the rupture areas of the Huatulco and 1978 earthquakes. Figs. 9c and 9d show the percentages of these contributions only where the total CFS is positive in Fig. 8a (i.e. where there was an effective increase of the earthquake potential). We can see that the rupture zones of the Huatulco and 1978 earthquakes (Regions A and B, Figs. 9a and 9b) are actually representative of the accumulation and partitioning of stresses between 20-35 km depth in all but the western segment of the region. We can also see that although most of the accumulated stress (i.e. ~75-85%) was generated by coupled interface regions, 15-25% was due to the SSEs and the afterslip (of the 2018 Pinotepa earthquake) occurring in the region over the 3.5 years period.

5. Discussion

The segment of the plate interface where the Huatulco earthquake ruptured has been characterized with moderate coupling (Fig. S10) (Radiguet et al., 2016; Rousset et al., 2016). Previous M7 class interplate earthquakes have occurred very close to it, such as the 1965 and 1928 events, suggesting a possible reactivation of the same asperity over time (Chael and Stewart, 1982; Singh et al., 1984). Historical data also suggest that two older, probably thrust earthquakes with magnitude larger than 7 occurred nearby in 1870 and 1801 (Suárez et al., 2020). Assuming that all these events broke the same plate interface patch, their average return period would be ~55 +/- 13 years. In this region also occurred the Mw ~8.6 San Sixto earthquake in 1787 over a ~300 km along-strike segment producing a great tsunami offshore Oaxaca (Ramírez-Herrera et al., 2020; Suárez and Albini, 2009). Such event must have involved the rupture of several locked segments along the Oaxaca megathrust including offshore shallow portions of the plate interface to generate the mega-tsunami. Whether M8+ events may repeat depends, among other factors, on the interplate friction and constructive stress interaction between different locked and unlocked fault segments (Kaneko et al., 2010; Kaneko et al., 2018), which continuously change over time. Recent laboratory experiments and theoretical fault models strongly suggest that the friction is a sensitive function of the interplate slip velocity where SSEs take place (Im et al., 2020). Then, since the slip velocity changes over time, these variations should be essential for the dynamic stability of the megathrust because of both their frictional counterparts and the associated stress changes documented here for the Oaxaca subduction zone. To have an insight into the actual earthquake potential (e.g. to assess whether adjacent locked segments are likely to break jointly to produce a much larger event) it is therefore necessary a proper and continuous quantification of the stress accumulation as proposed here. Monitoring the interplate slip-rate continuously might also allow us to constrain the evolution of the frictional parameters that determine the slip stability regime on the megathrust.

An interesting feature of the Huatulco earthquake is that rupture did not propagate into the adjacent updip segment (above ~17 km depth) that should also be locked. Impeding the rupture propagation into that segment might be associated with the interface geometry (e.g. due to subducted plate reliefs as recently proposed in the Guerrero seismic gap (Plata-Martínez et al., 2020)), the frictional conditions and/or, as shown in this investigation, with the existence of a significantly-large stress barrier due to both the stress shadow produced by nearby strongly coupled zones and persistent small SSE occurring updip. The spatial distribution of aftershocks during the first 50 days following the Huatulco event is clearly shifted updip (about 30 km) from the rupture area, where the afterslip developed and the CFS strongly increased. Only very few aftershocks lie within the main slip patch, indicating an effective stress release within the most of the rupture area, which is consistent with other M7 class earthquakes observed worldwide (Wetzler et al., 2018). Furthermore, the earthquake nucleation in the shallowest part of the rupture zone and northward propagation can also be explained by our model due to the localized increments of CFS right in the nucleation zone over the six months prior to the earthquake (Supplementary Movie S1) and the longer-term stress accumulation downdip the hypocenter (Figs. 7a and 8a), respectively.

We find that strongly coupled regions in Oaxaca are highly variable in space and time before and after the occurrence of the Pinotepa and Huatulco earthquakes. These remarkable PIC variations might be associated with abrupt changes in the mechanical properties of the fault zone materials induced by the dynamic perturbations of the seismic waves from the earthquakes (Cruz-Atienza et al., 2020; Materna et al., 2019). Furthermore, we observed that the PIC changes are somehow linked to nearby SSEs that occur in the region (Figs. 6a and S9a). To explain these short-term variations of the PIC at seismogenic depths, we favor models involving fluctuations of fluid pressure as proposed for the long-term SSEs in the Guerrero subduction zone (Cruz-Atienza et al., 2018), in southern Cascadia (Materna et al., 2019) and the Hikurangi subduction zone (Warren-Smith et al., 2019). Recently, models evoking the fault-valving concept show overpressure pulses migrating upward along the fault as the permeability evolves in the fault zone (Cruz-Atienza et al., 2018; Shapiro et al., 2018; Zhu et al., 2020). These transient changes in pore pressure may lead to large variations of the fault strength as high as ~10-20 MPa (Zhu et al., 2020), which makes this mechanism a plausible candidate to explain the strong PIC variations in the seismogenic zone of Oaxaca during the occurrence of SSEs and earthquakes.

Earthquake potential depends on the state of stress along the subduction zone that, as shown here, is a function of different evolving processes taking place from the trench to its deep portion where the plates mechanical interaction ceases. The stress build-up therefore changes over time and space in a complex way, so does the earthquake potential. Time-invariant estimates of the interplate coupling are often used to identify seismogenic segments that are prone to large earthquakes (Chlieh et al., 2008; Loveless and Meade, 2011; Moreno et al., 2010; Perfettini et al., 2010). However, while these estimates are certainly useful on a large spatial and temporal scale, they do not provide a reliable picture of the earthquake potential associated with smaller ($7 < M < 8.5$) but potentially devastating ruptures that occur more frequently, as shown in this work for the Oaxaca megathrust.

Our results indicate that continuously monitoring the interplate slip velocity provides a better reconstruction of the stress development on the seismogenic region. Systematic and simultaneous observation of PIC and the relaxing slip (SSE and afterslip) over the plate interface is thus very relevant to evaluate theoretical predictions of the interface dynamics, which is our leading approach to understand the underlying physics in subduction systems.

6. Conclusions

We analyzed the interplate slip-rate evolution during 3.5 years in the Oaxaca subduction zone including the pre-seismic, coseismic and post-seismic phases associated with the June 23, 2020 Mw 7.4 Huatulco earthquake to understand how the different slip processes contribute to the plate-interface stress accumulation in the region. We found that the main rupture area of the Huatulco earthquake extents between 20 and 30 km depth with two main and compact slip patches, the most prominent north the hypocenter and a much smaller close to the coast, east-northeast of the hypocenter. The 2020 SSE that occurred before the earthquake did not penetrate the rupture area and was preceded by a gradual interface decoupling process at a regional scale, including the maximum SSE slip area. During the two months preceding to the earthquake, when the 2020 SSE developed, the Huatulco earthquake rupture area became fully locked. Our slip inversions indicate that the two-month earthquake afterslip overlapped the whole coseismic rupture area and propagated both to the trench and to the northwest, where most of aftershocks happened and where the 2020 SSE was developing as well as previous SSEs have occurred in the region, respectively. During the post-seismic phase, the rupture area of the 1978 Puerto Escondido earthquake became and remained fully coupled. The interplate slip-rate evolution in Oaxaca during the 3.5 years preceding the Huatulco earthquake shows that the PIC in the megathrust seismogenic region is highly variable in time and space, and that the PIC reductions over the Huatulco and the 1978 rupture areas are well correlated with the occurrence of SSEs further downdip, clearly suggesting a physical relationship between both processes. We found that both stress-relaxing aseismic slip events and megathrust coupling changes produced a region of high stress accumulation where the main asperity of the Huatulco earthquake broke as well as a shallow stress deficit region that probably impeded the updip propagation of the earthquake. Our results suggest that continuous monitoring of the interplate aseismic slip-rate and its CFS counterpart provides a better estimation of the earthquake potential on locked seismogenic regions than predictions given by time-independent interplate coupling models. Finally, the stress imparted during the coseismic and postseismic phases of the Huatulco earthquake on the 1978 rupture area make it a region very prone to the next earthquake in the nearest future, which is consistent with the ~50 years earthquake return period in the Oaxaca region.

Declaration on competing or conflict of interest

The authors have no competing or conflict of interest in what is expressed in this manuscript.

CRediT authorship contribution statement

C. Villafuerte: Conceptualization, Methodology, Investigation, Formal Analysis, Writing-Original Draft, Visualization. **V.M. Cruz-Atienza:** Conceptualization, Methodology, Investigation, Formal Analysis, Visualization, Writing-Review & Editing, Supervision. **J. Tago:** Methodology, Investigation, Software, Validation, Review & Editing. **D. Solano-Rojas:** Investigation, Validation, Data processing, Review & Editing **R. Garza-Girón:** Investigation, Visualization, Data processing, Review & Editing **S.I. Franco:** Data processing, Editing. **L.A. Dominguez:** Investigation, Editing. **V. Kostoglodov:** Investigation, Review & Editing.

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Figures

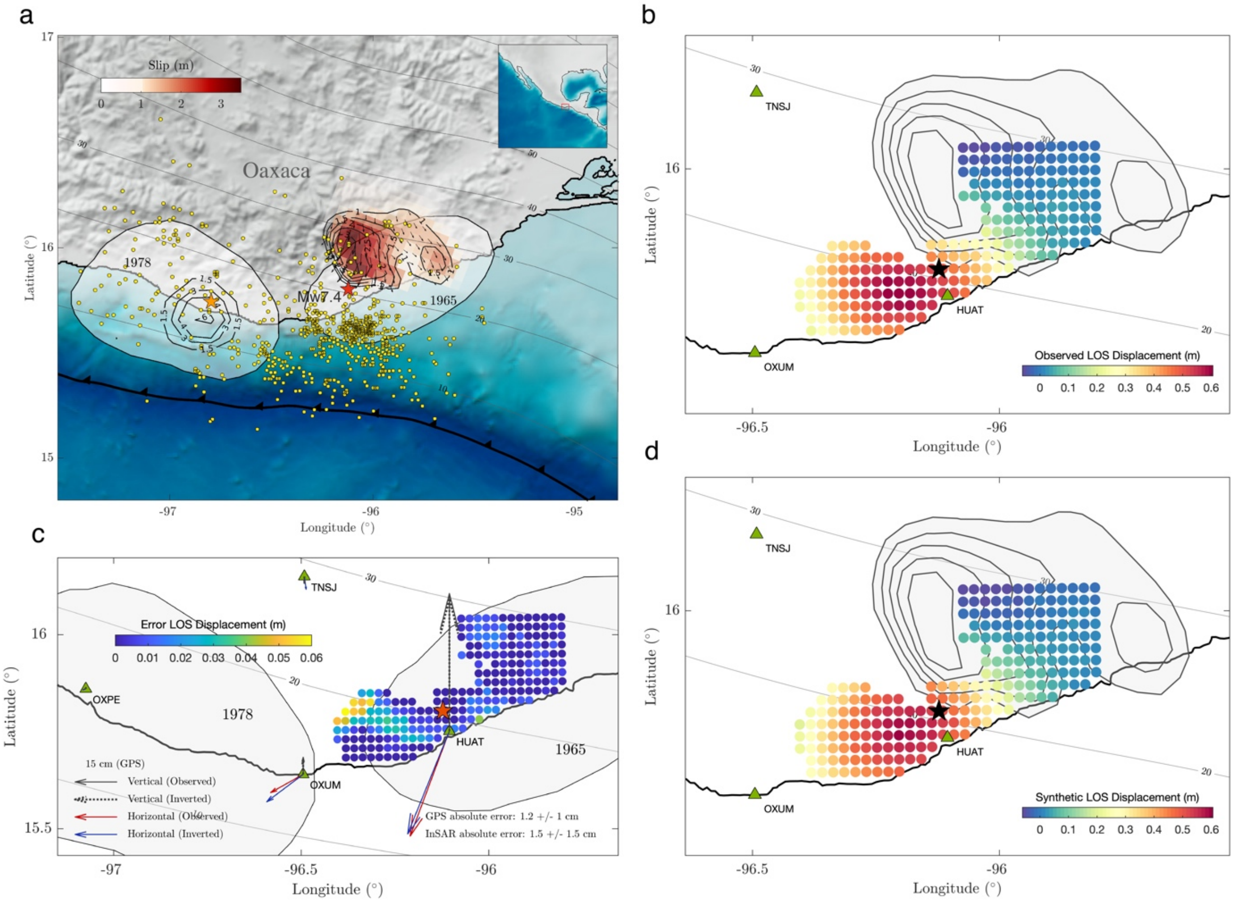


Fig. 1 Coseismic slip inversion results for the 2020 Mw 7.4 Huatulco earthquake. **a** Red colored region with black contours indicates the slip on the plate interface for our preferred joint GPS and InSAR slip inversion. Red and orange stars indicate the epicenters of the Huatulco and the 1978 Puerto Escondido earthquakes, respectively. Black contours around the 1978 Puerto Escondido hypocenter represent the 1.5, 3, 4 and 6 m slip isolines from Mikumo et al. (2002). White shaded patches show the aftershock areas of the historic interplate earthquakes in 1965 and 1978. Yellow dots depict the 50 days aftershocks reported by the SSN. Gray contours indicate the iso-depths of the 3D plate interface used for the slip inversions in this study. **b** and **d** show the observed and synthetic line of sight (LOS) displacements, respectively. **c** Misfit between observed and predicted LOS displacement and GPS surface displacements. Red and blue arrows show the observed and synthetic horizontal displacements from the GPS data. Continuous and dashed arrows indicate the observed and synthetic vertical displacement, respectively.

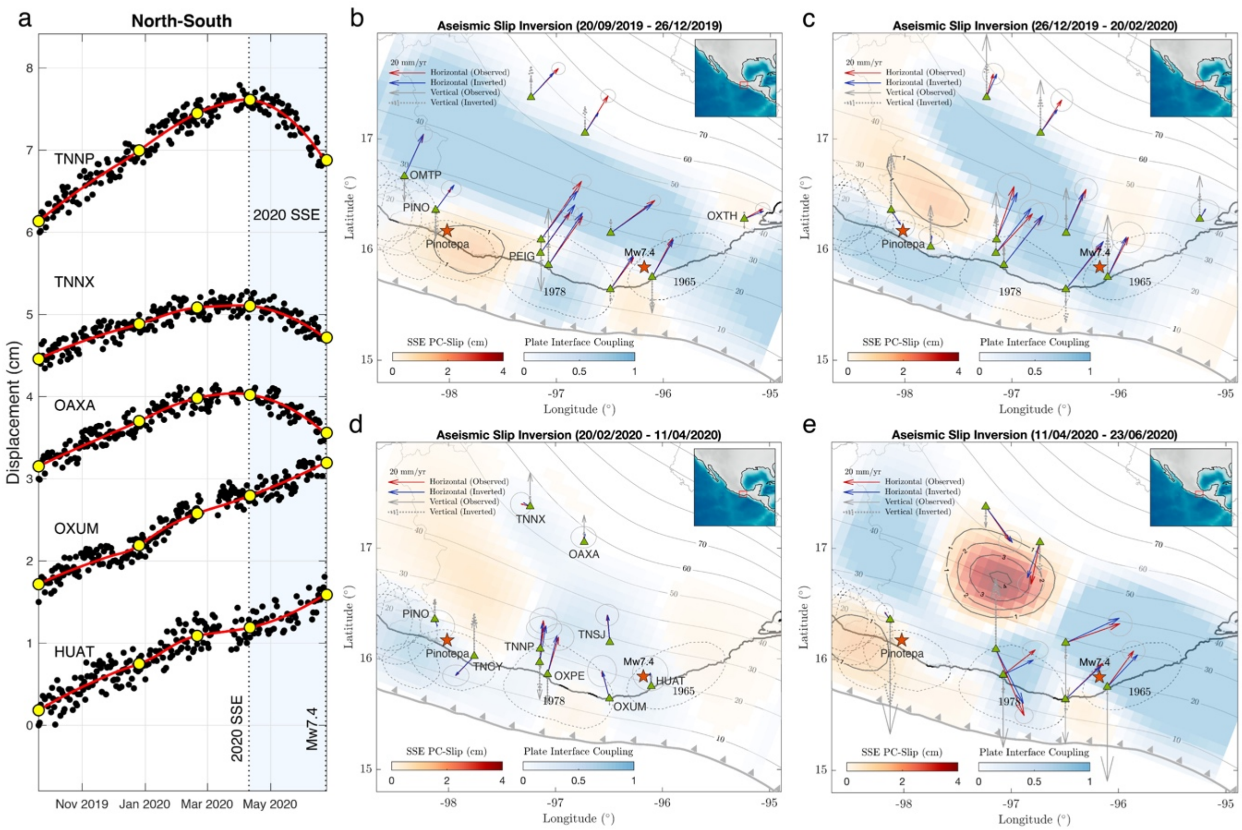


Fig. 2 GPS inversions of the pre-seismic deformation period during the two months preceding the Huatulco earthquake. **a** North-south displacement GPS time series in 5 selected stations. Yellow dots indicate the start and the end of the four time-windows used for the slip inversions shown in **b-e**. **b-e** Aseismic slip inversion for the 9 months deformation preceding the Huatulco earthquake. Red star depicts the epicenter of the earthquake. Slip contours are in centimeters. Dashed regions are the aftershock areas of historic interplate earthquakes. Red and blue arrows show the observed and synthetic horizontal displacements and the gray ellipses are their one standard deviations. Solid and dashed arrows indicate the observed and synthetic vertical displacement, respectively.

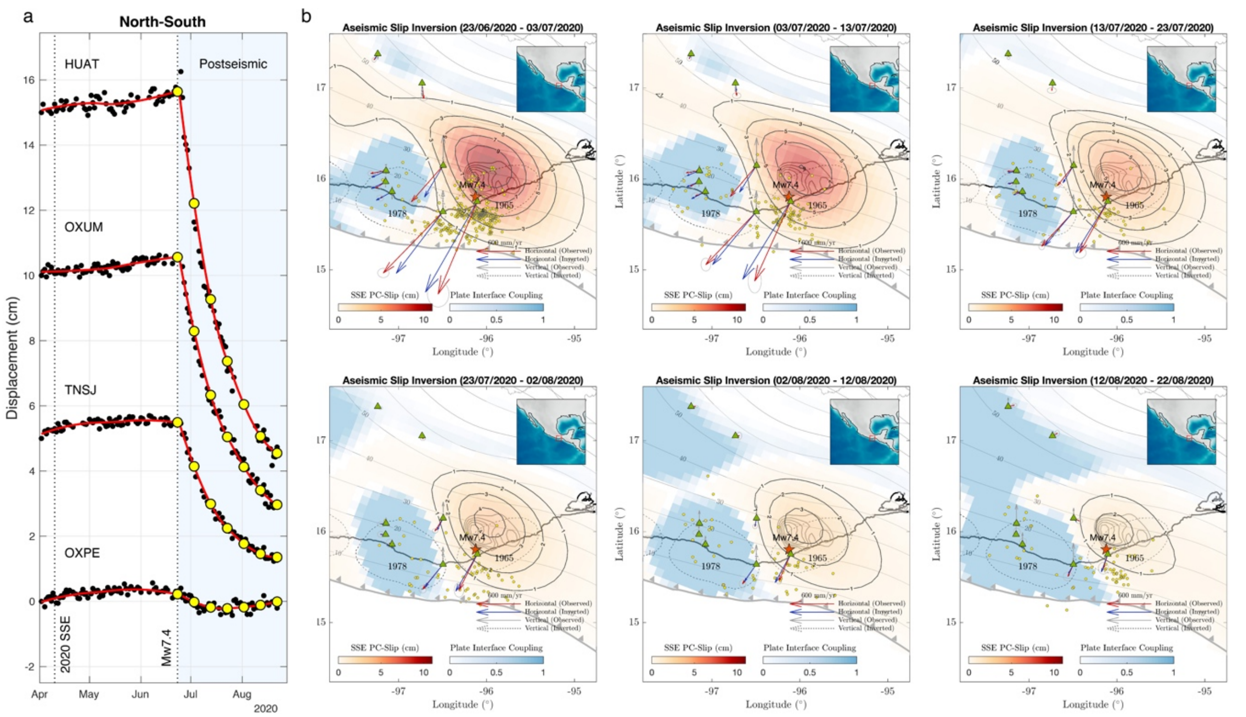


Fig. 3 GPS inversion of the postseismic deformation of the Huatulco earthquake. **a** North-south displacement GPS time series in 4 selected stations. Yellow dots indicate the start and the end of the six 10-day windows used for the slip inversions shown in **b**. **b** Aseismic slip inversion for the two months following the Huatulco earthquake. Yellow dots represent the aftershocks that occurred during the inversion time-window. Red star depicts the hypocenter of the Huatulco earthquake. Slip contours are in centimeters. Thick light gray contours are the coseismic slip shown in figure **1a**. Dashed regions are the aftershock areas for the 1978 and 1965 historic interplate earthquakes. Red and blue arrows show the observed and synthetic surface displacements, and the gray ellipses one standard deviation of the GPS displacements. Continuous and dashed arrows indicate the observed and synthetic vertical displacement, respectively.

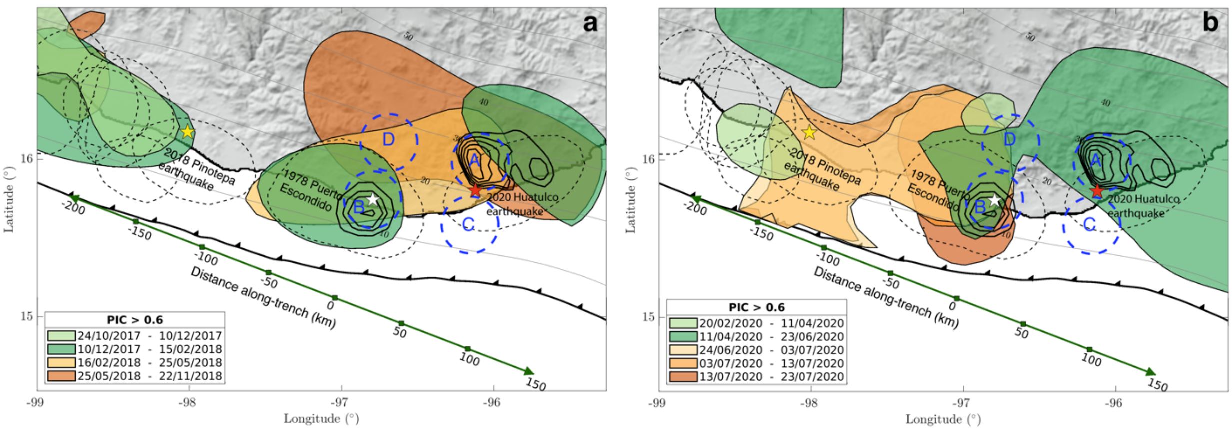


Fig. 4 Evolution of interplate strong interplate coupled regions around the rupture areas of interplate earthquakes in Oaxaca. **a** Evolution of regions with PIC > 0.6 before (green patches) and after (warm color patches) the 2018 Mw 7.2 Pinotepa earthquake. Red, orange and yellow stars indicate the hypocenter of the Huatulco, the 1978 Puerto Escondido and the 2018 Pinotepa earthquakes, respectively. Black contours represent the slip isolines of the Huatulco and 1978 Puerto Escondido earthquakes (Mikumo et al., 2002). Dashed blue circles represents the areas with radio of 20 km where we analyze the evolution of the interplate slip rate and the CFS shown in figures 6, 7c and 7d. **b** Same than **a** but for the 2020 Mw. 7.4 Huatulco earthquake. Green line indicates the along-trench profile where the evolution of the aseismic slip and CFS on the plate interface is analyzed in Figs. 5,7 and 8.

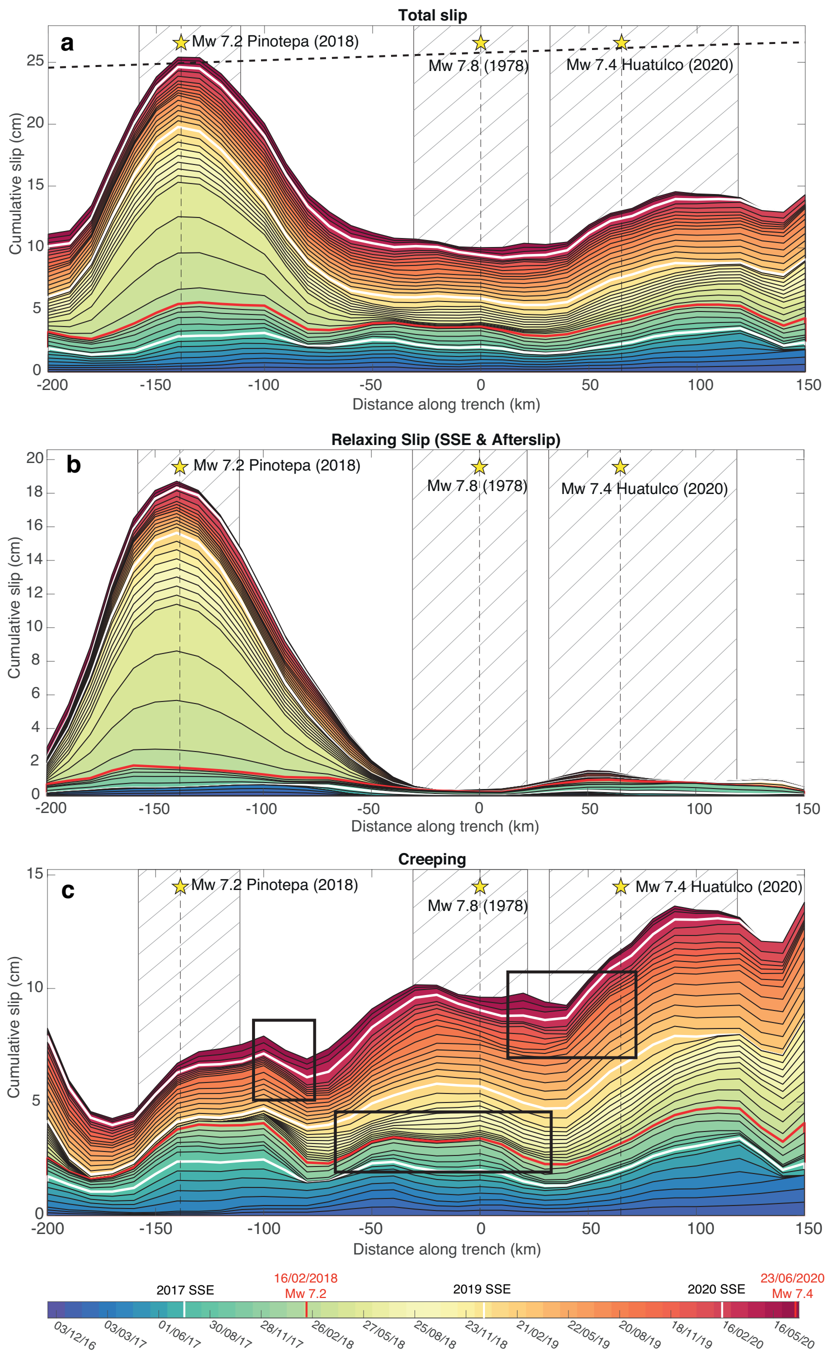
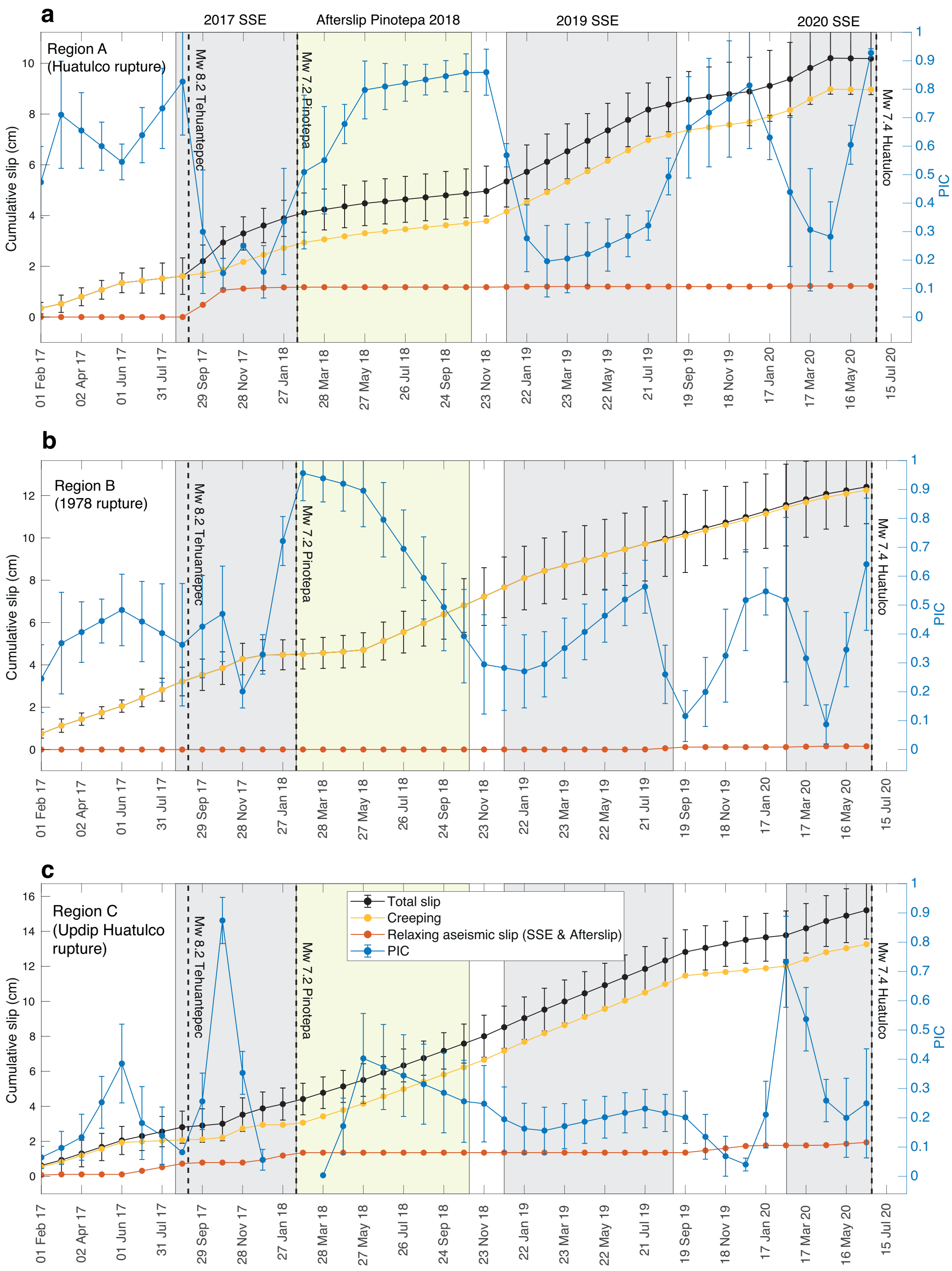


Fig. 5 Evolution of the interplate aseismic slip along the trench within the seismogenic zone of the Oaxaca subduction zone. Bottom color scale shows time. Evolution of the **a** total aseismic slip (relaxing aseismic slip + creeping), **b** the relaxing aseismic slip (SSEs and afterslip) and **c** the creeping (regions in coupling regime) averaged between 10-30 km depth. Hatched regions show the interplate segments with the highest moment release of the 2018 Pinotepa, 1978 Puerto Escondido and 2020 Huatulco earthquakes. Stars and dashed black lines indicate the along-trench coordinate of the hypocenters. White curves indicate the time when the last three long-term SSE began in Oaxaca and the red curve indicates the rupture time of the 2018 Pinotepa earthquake. Black rectangles enclose the episodes with significant variations of the slip velocity (see text). Dashed oblique line in **a** represents the expected total displacement of the incoming Cocos plate during the whole period shown by the colorbar.



05
06 **Fig. 6** Detailed evolution of the aseismic slip in the seismogenic segment of Oaxaca. Evolution of the
07 cumulative total slip, creeping, relaxing aseismic slip and plate interface coupling in (**a**) Region A (the
08 Huatulco rupture area), (**b**) Region B (the 1978 Puerto Escondido rupture area) and for (**c**) Region C (updip
09 region of the Huatulco earthquake). Gray rectangles indicate the occurrence of SSEs in the region. The light-
10 yellow rectangle shows the period when the 2018 Pinotepa earthquake afterslip developed in the region.
11

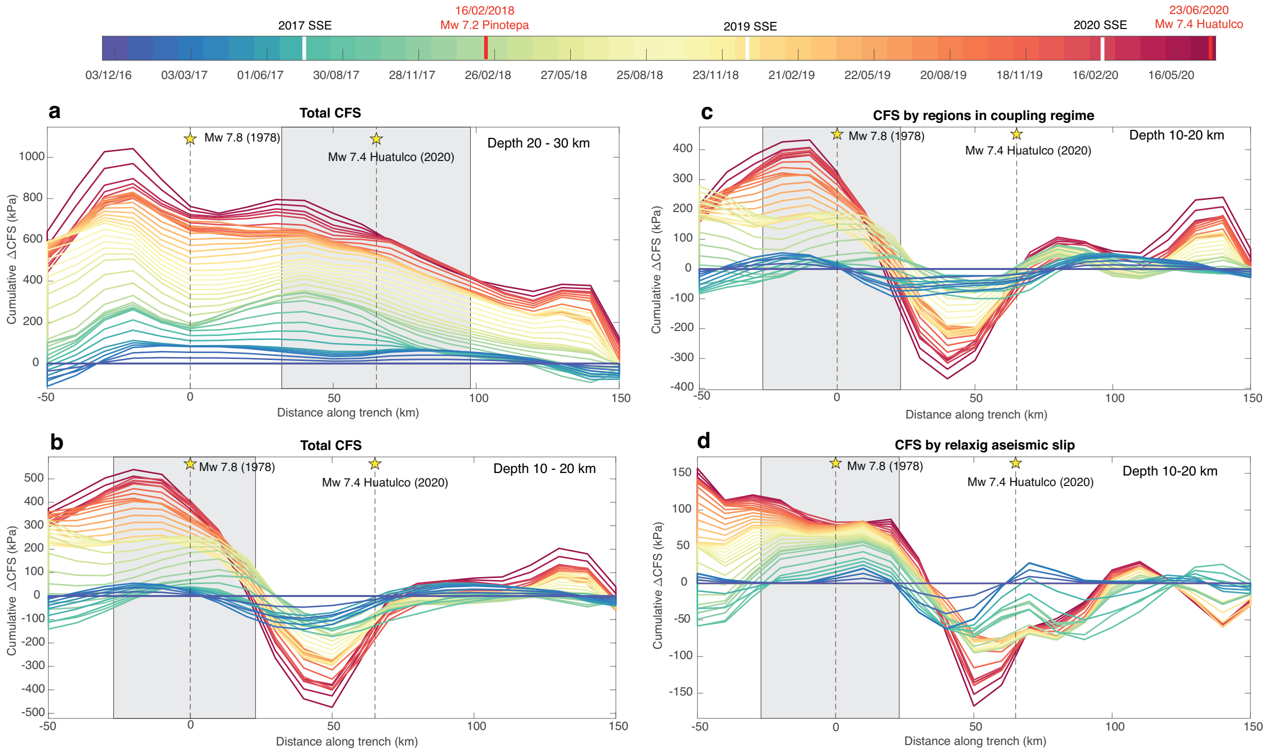


Fig. 7 Evolution of the CFS in the seismogenic segment of Oaxaca. Evolution of the total CFS along the trench for every 30 days averaged between **a** 20-30 km and **b** 10-20 km depth. Gray rectangles show the interplate segments with the highest moment release of the 2020 Huatulco earthquake and the 1978 Puerto Escondido event (Mikumo et al., 2002). **c** and **d** shows the evolution of the CFS for the band between 10-20 km depth split into the contributions from regions in coupling regime and the relaxing aseismic slip, respectively.

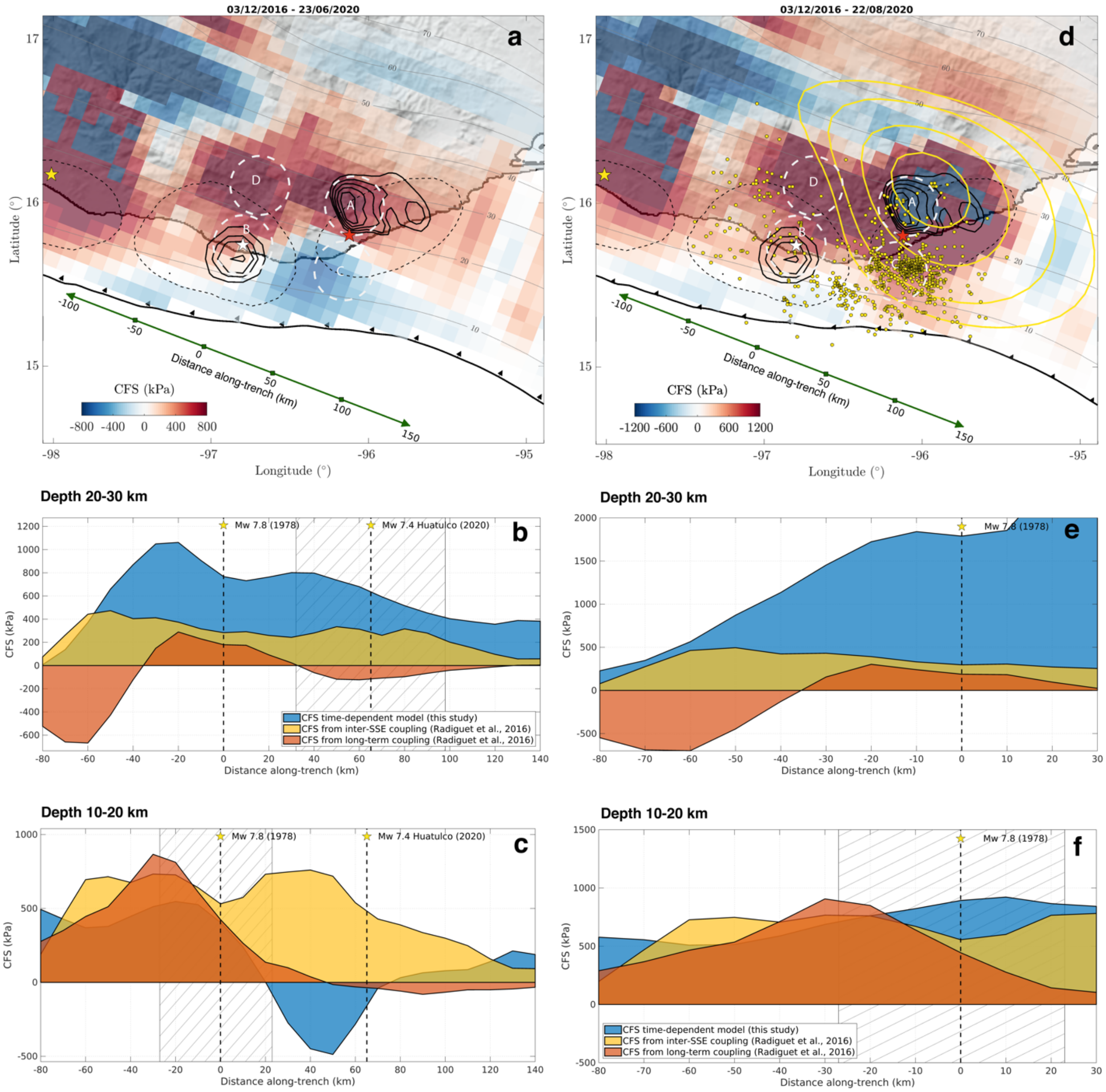


Fig. 8 Cumulative CFS from the time-variant model and its comparison with the stress built up predicted by time-invariant coupling models. **a** Cumulative CFS in the plate interface between December 2017 and the date of the 2020 Huatulco earthquake. Black contours represent the isoslip values for the 2020 Huatulco and 1978 Puerto Escondido (Mikumo et al., 2002) earthquakes. Black dashed lines delimit the aftershock areas of historic interplate earthquakes. White dashed circles represent the regions where we analyze the evolution of the interplate slip rate and the CFS shown in figures 6, 7c and 7d. **b, c** Comparison between our cumulative CFS time-variant model and the CFS predicted by time-invariant coupling models of the region (Radiguet et al., 2016) between December 2017 and the date of the 2020 Huatulco earthquake for two depth bands, between 20-30 km depth and between 10-20 km depth, respectively. **d** Same than **a** but including the stress contributions from the coseismic and postseismic phases of the Huatulco earthquake. Yellow contours are the 5,10,20 and 30 cm slip isolines of the two months cumulative afterslip. Yellow dots depict the 50 days aftershocks after the Huatulco Earthquake reported by the SSN. **e,f** Same as **b,c** but including the stress contribution from the coseismic and postseismic phases of the Huatulco earthquake focused only in the 1978 rupture segment.

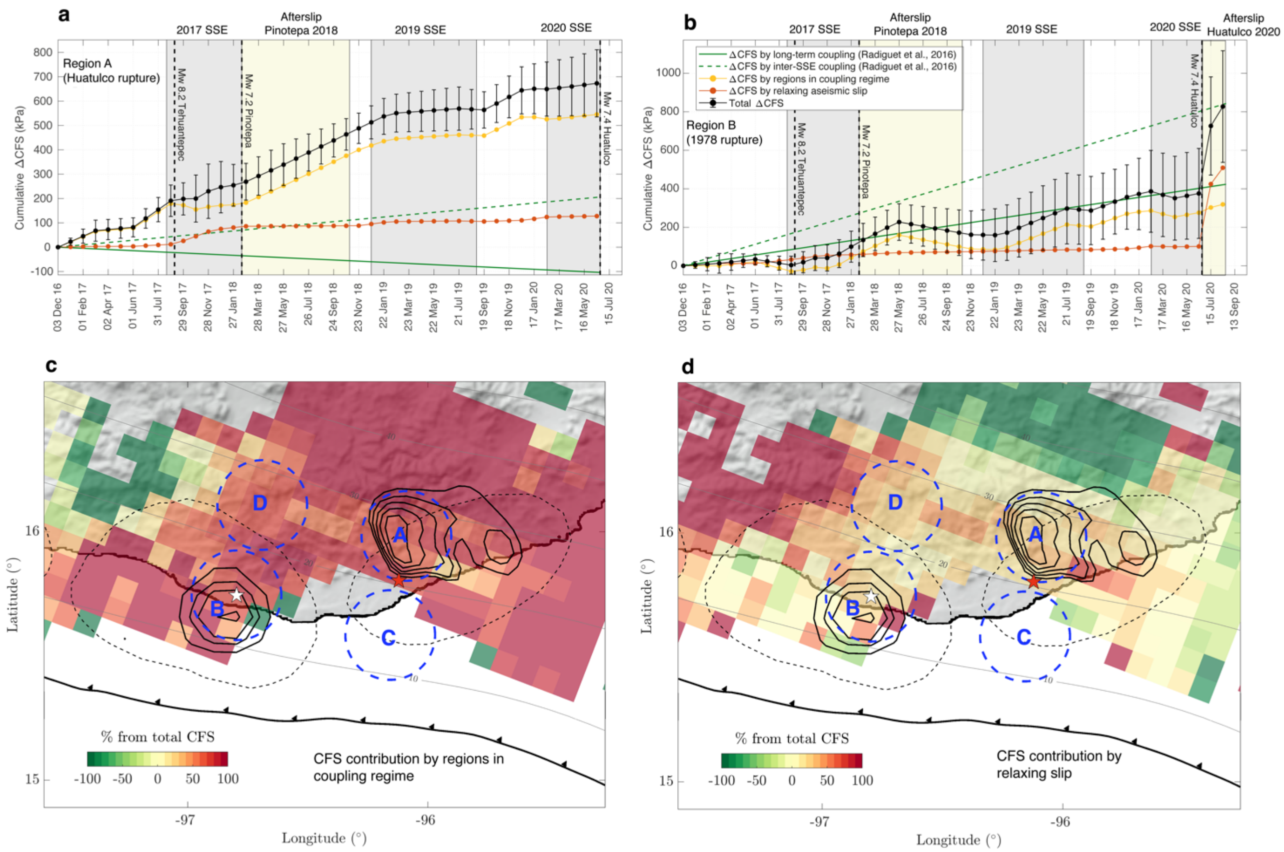


Fig. 9 CFS contributions by regions in coupling regime and relaxing slip. **a** and **b** show the evolution of the total CFS (black curves) and their contributions from the relaxing aseismic slip (red curve) and coupled regions (yellow curve), for the Region A (the Huatulco rupture area) and the Region B (the 1978 Puerto Escondido rupture area), respectively. Gray rectangles indicate the occurrence of SSEs in the region. The light-yellow rectangle shows the period when the postseismic afterslip of the 2018 Pinotepa and 2020 Huatulco earthquakes developed in the region. **c** and **d** show the CFS contributions (in %) on the plate interface where the total CFS is positive (see figure 8a) by regions in coupling regime and relaxing slip, respectively.

Supplementary Materials for:

Slow slip events and megathrust coupling changes reveal the earthquake potential before the 2020 Mw 7.4 Huatulco, Mexico, event

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This document includes:

Methods:

1. GNSS time series processing.
2. InSAR images processing.
3. Slip inversion method.
4. Coulomb Failure Stress estimation.

Supplementary Figures S1-S11

Methods

1. GNSS time series processing

The GNSS displacement times series are estimated using the GIPSY 6.4 software package (Lagler et al., 2013), which follows a Precise Point Positioning strategy. The station positions are defined in the International Terrestrial Reference Frame, year 2014 (ITRF 2014). For daily processing we used the Jet Propulsion Laboratory final and non-fiducial products (orbits and clocks). We generated observables using 2 model categories: (1) Earth models and (2) observation models. The Earth models include tidal effects (i.e. solid tides, ocean loading and tide created by polar motion), Earth rotation (UT1), polar motion, nutation and precession. Observation models, on the other hand, are related with phase center offsets, tropospheric effects and timing errors (i.e. relativistic effects). The troposphere delay is estimated like as random walk process. This effect is broken into wet and dry components. The azimuthal gradient and the dry component are estimated using GPT2 model and mapping function (TGIPSY1). The antennas phase center variations are considered through antenna calibration files. For receiver antennas, the correction is estimated taking the International GNSS Service (IGS) Antex file. We also applied a wide-lane phase bias to account for the ambiguity resolution.

To remove the outliers and then estimate the displacement vectors per time window, we first determine the data variance for each component and time window from the differences between daily displacement values and a moving, locally weighted LOESS function (i.e. 2nd order polynomial regressions with a half-window time support, Figs. 2a, 3a and S6). Then, all data points in a time window with differences larger than one standard deviation were dismissed. Once the outliers are removed, a new regression is performed to estimate the final displacement vectors.

2. InSAR images processing

We calculate a coseismic interferogram of the Huatulco Earthquake using two single look complex Synthetic Aperture Radar (SAR) scenes acquired by the Sentinel-1 satellites in the Interferometric Wide Swath acquisition mode, ascending pass, track 107 (Fig. S2a). The selected scenes were acquired on June 19th and June 25th, 2020, which correspond to the pair with the shortest-possible acquisition span (6 days). The pass and track were selected to provide the best-possible coverage of the coseismic signal. We use the processing chain provided in the InSAR Scientific Computing Environment (ISCE) (Rosen et al., 2012) to calculate the interferometric phase between the two SAR scenes, which includes a coarse coregistration assisted by a digital elevation model (DEM), a coarse inteferogram calculation, a fine coregistration, a fine inteferogram calculation, and basic phase corrections. Accordingly, we additionally use a 1 arc-second DEM from the Shuttle Radar Topography Mission (Farr et al., 2007) to complete the interferogram formation and topographic phase correction. Subsequently, we filter the interferometric phase using a Goldstein filter (Goldstein & Werner, 1998) to later perform phase unwrapping using SNAPHU (Chen & Zebker, 2000). We finally geocode the unwrapped interferogram, convert it to displacement in meters in line of sight (LOS) geometry and mask out water bodies and areas with spatial coherence lower than 0.4 (Fig. S2b).

Geodetic measurements from GNSS and InSAR have different reference frames, which requires converting one into the other to make a fair comparison of the displacements obtained by each technique. GNSS measurements are referenced in East, North and Up components, whereas satellite InSAR have a pixel-wise reference frame in terms of incidence (θ) and azimuth (α) angles, which vary pixel by pixel and define the relative LOS direction towards the SAR satellite. GNSS displacements can be projected onto the satellite's LOS direction following the expression (Hanssen, 2001):

$$GPS_{LOS} = -\sin\left(\alpha - \frac{3\pi}{2}\right) \sin\theta d_e - \cos\left(\alpha - \frac{3\pi}{2}\right) \sin\theta d_n + \cos\theta d_u$$

where GPS_{LOS} is the projection of the GNSS displacement vector onto the LOS vector, and d_e, d_n and d_u are the GNSS displacement components in the East, North and Up directions, respectively. Based on this transformation we adapted the ELADIN inversion method (see next section) so that the Somigliana tensor used to generate the synthetic displacements was projected into the individual LOS unit vectors per InSAR data point to perform the simultaneous GNSS and InSAR data inversion.

3. Slip inversion method

The ELADIN (ELastostatic ADjoint INversion) method (Tago et al., 2020) solves a constrained optimization problem based on the adjoint elastostatic equations with Tikhonov regularization terms, a von Karman autocorrelation function and a gradient projection method to guarantee physically-consistent slip restrictions. The method simultaneously determines the distribution of PIC and relaxing slip (i.e. SSEs and afterslip) in the plate interface to explain the surface displacements. Its precision matrix, which corresponds to the inverse of the data variance matrix (see Section 1), allows to minimize the effect of data errors (i.e. cumulative processing errors and non-tectonic physical signals) by weighting the observations. For the pre-seismic and post-seismic GNSS inversions (Figs. 2 and 3), the weights are given directly by the data variance matrix per time window and displacement component (i.e. ellipses around the tips of the horizontal displacement vectors in Figures 2 and 3) (Tago et al., 2020). For the coseismic analysis, where GNSS and InSAR displacements are simultaneously inverted (Figs. 1 and S3c), the data weights were determined by trial and error. The final optimal set of values are such that all InSAR data (i.e. the 221 LOS displacements, Figs. 1b and S2c) were attributed a weight equal to one, while the GNSS data (i.e. 12 displacement components) were weighted according to the epicentral distance of each station as follows. The HUAT and OXUM sites weighed 25, the TNSJ site weighed 15, and the OXPE site weighed 5, with these values being the same in all three components per site.

For the coseismic slip inversion, we determined an optimal correlation length of 7 km and a Hurst exponent of 0.75 for the von Karman inverse-problem regularization function and restricted the slip component perpendicular to the plate convergence direction to be smaller than 0.6 m (for details see Tago et al. (2020)). For the pre- and post-seismic slip inversion, we assumed the same Hurst exponent for the von Karman regularization function, but with correlation length of 40 km to guarantee high slip restitution in the whole region (Cruz-Atienza et al., 2020; Tago et al., 2020).

As for the inversion exercise we performed to match the relocated hypocentral depth of 17.2 km, the results (Fig. S4) significantly improved the data fit (i.e., average errors of 0.7 ± 0.6 cm and 0.1 ± 1.4 cm for GNSS and InSAR data, respectively) and reproduced source characteristics similar to those of our preferred solution discussed in the main text, which assumes a 3.5 km deeper interface (Figs. 1a and S3c). However, it is important to point out some differences with that source model: (1) the maximum slip is significantly larger (4.3 m), (2) the moment magnitude is smaller (Mw 7.3) as determined from the 1 m slip contour, and (3) the rupture is more concentrated in the main patch north of the hypocenter, between 18 and 30 km deep. To be consistent with the following sections (i.e., to use the same interface geometry throughout the manuscript), we keep the deeper solution shown in Figure 1 for subsequent analysis.

4. Coulomb Failure Stress estimation

The total static stress change on the plate interface is the sum of the stress contributions from plate interface regions that slip, producing either a stress relaxation on the continental crust (SSEs + coseismic slip + afterslip) or a stress built-up (regions in coupling regime that we modeled as backslip (Savage, 1983)). To estimate the stress tensor, we discretized the 3D plate interface into triangular subfaults and used the artefact-free triangular dislocation method introduced by Nikkhoo and Walter (2015) for a half-space. We then compute the Coulomb Failure Stress change (ΔCFS) induced on the plate interface by assuming a locally-consistent thrust mechanism following:

$$\Delta CFS = \Delta\tau + \mu\Delta\sigma_n$$

where $\Delta\tau$ represents the change of the shear stress in the direction of the fault slip (assumed to be parallel to the plate convergence direction (DeMets et al., 2010); $\Delta\sigma_n$ is the change of the fault normal stress (positive for tension); and μ is the apparent coefficient of friction assumed to be 0.5.

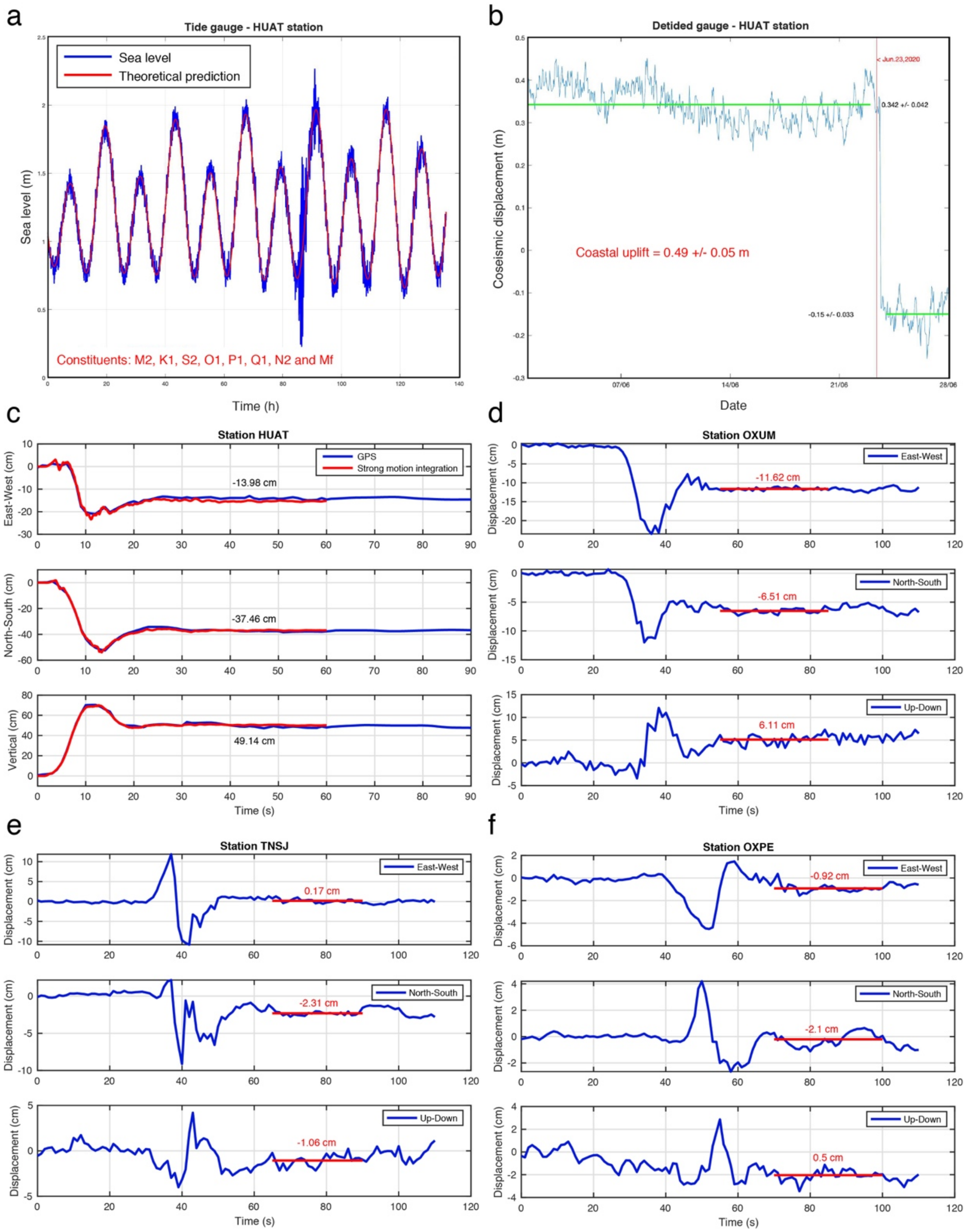

Fig. S1 Huatulco earthquake co-seismic displacements estimated from the HUAT tide gauge (**a** and **b**); high-rate GPS time series at stations HUAT (**c**), OXUM (**d**), TNSJ (**e**) and OXPE (**f**); and double integration of a strong motion record following the procedure of Wang et al. (2011)(red curve in **c**).

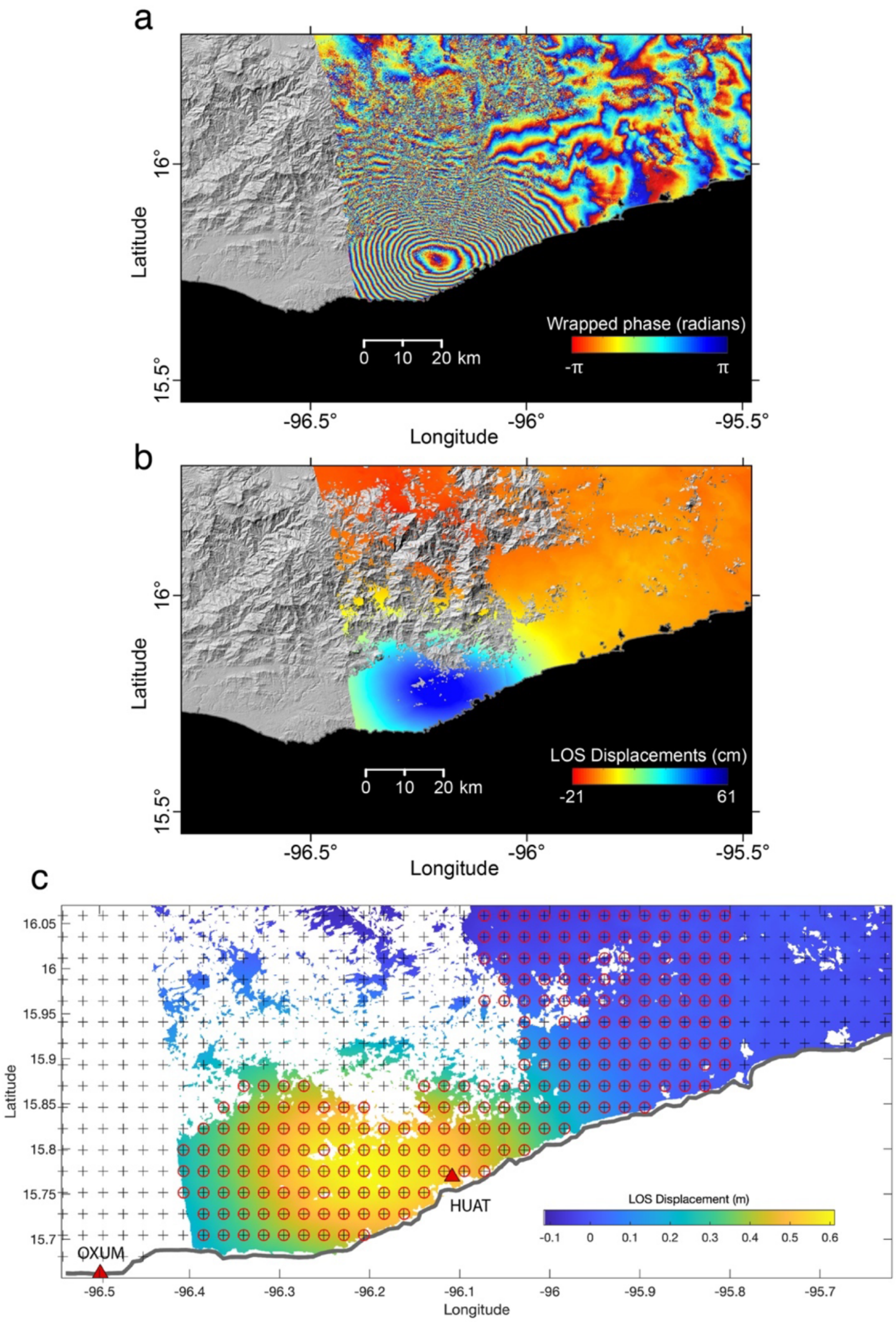

Fig. S2 Huatulco earthquake InSAR displacements estimated from Sentinel satellite images on Track 107 Ascending for scenes on June 19 and 25, 2020. **a** Wrapped phase ascending interferogram. **b** Line of sight (LOS) displacement from ascending track, positive values correspond to motion towards the satellite. **c** Same than **b** but showing the data (circles with crosses) used for the coseismic inversion.

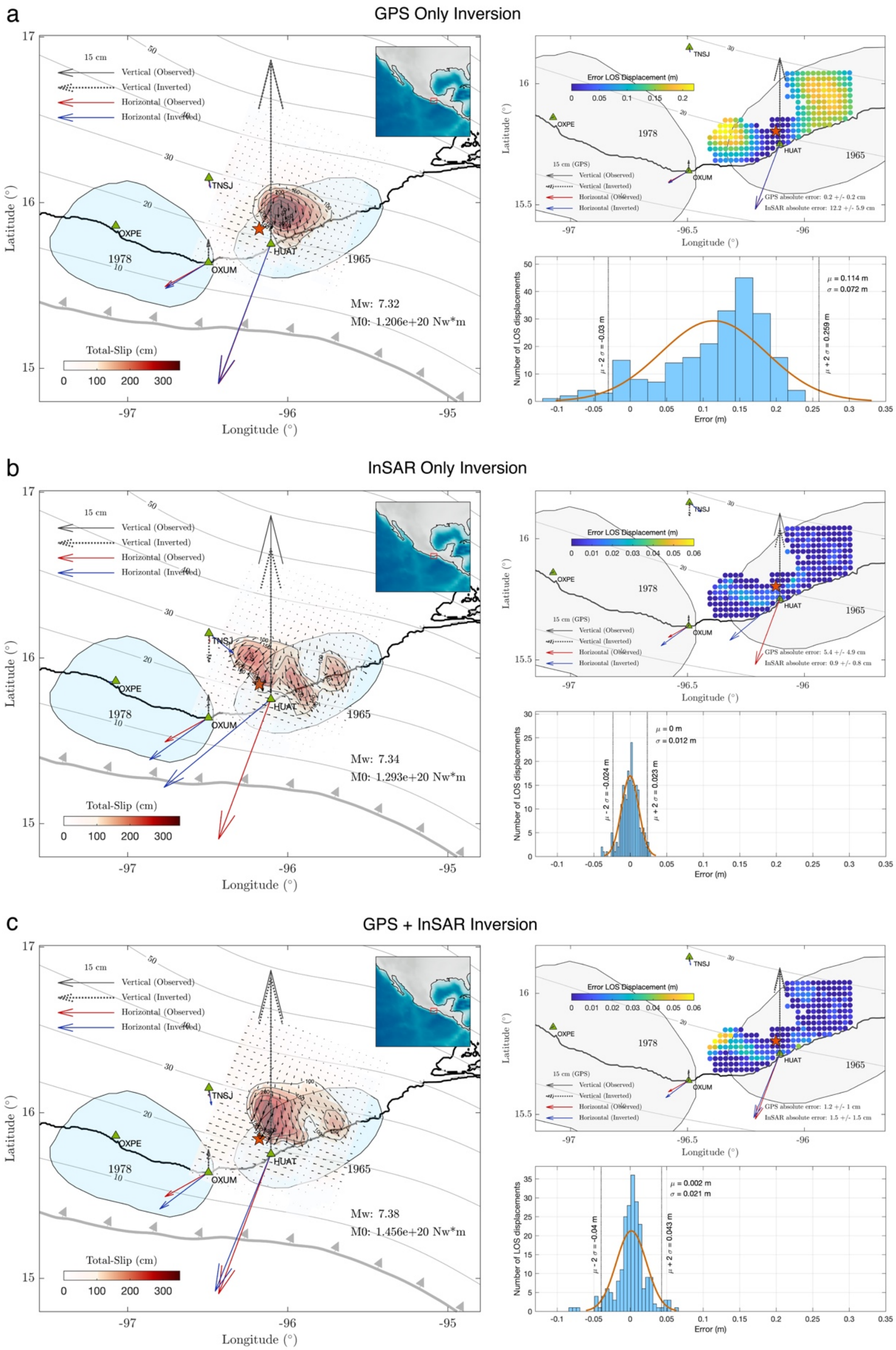

Fig. S3 Coseismic slip inversions for the Huatulco earthquake using different data sets. Coseismic slip inversion (left panel) and their associated misfit GPS and LOS displacements errors (right panels) using **(a)** only GPS data, **(b)** only InSAR data and **(c)** both GPS and InSAR data.

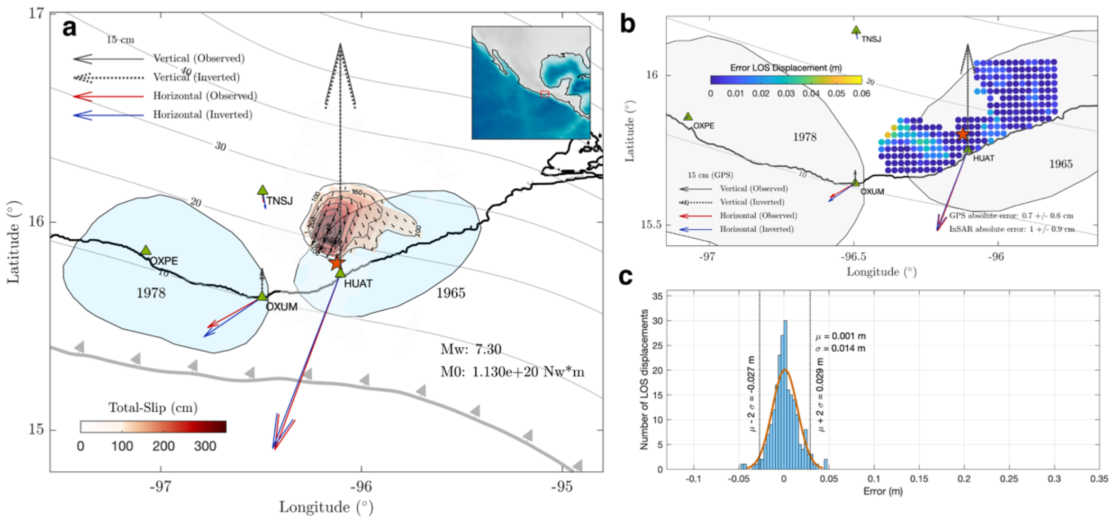

Fig. S4 Huatulco earthquake joint inversion (GNSS and InSAR) assuming that the plate interface has a depth of 17.2 km at the epicenter (i.e., shifted ~3.5 km upwards with respect to the interface shown in Figure S3). Coseismic slip inversion (**a**) and their associated misfit GPS and LOS displacements errors (**b** and **c**).

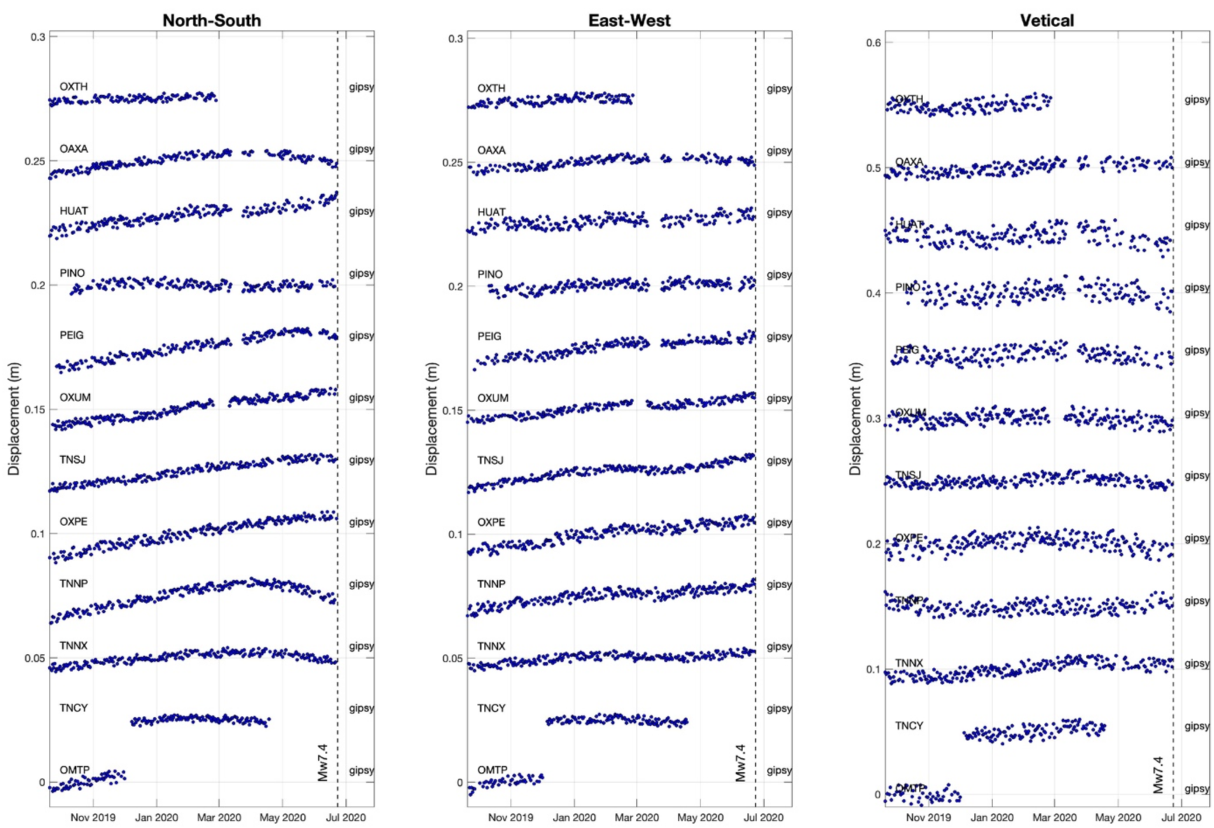

Fig. S5 GPS displacement time series estimated with the Gipsy-Oasis (v6.4) software for the pre-seismic period in the 12 stations and the three components. See Figures 2 and S6.

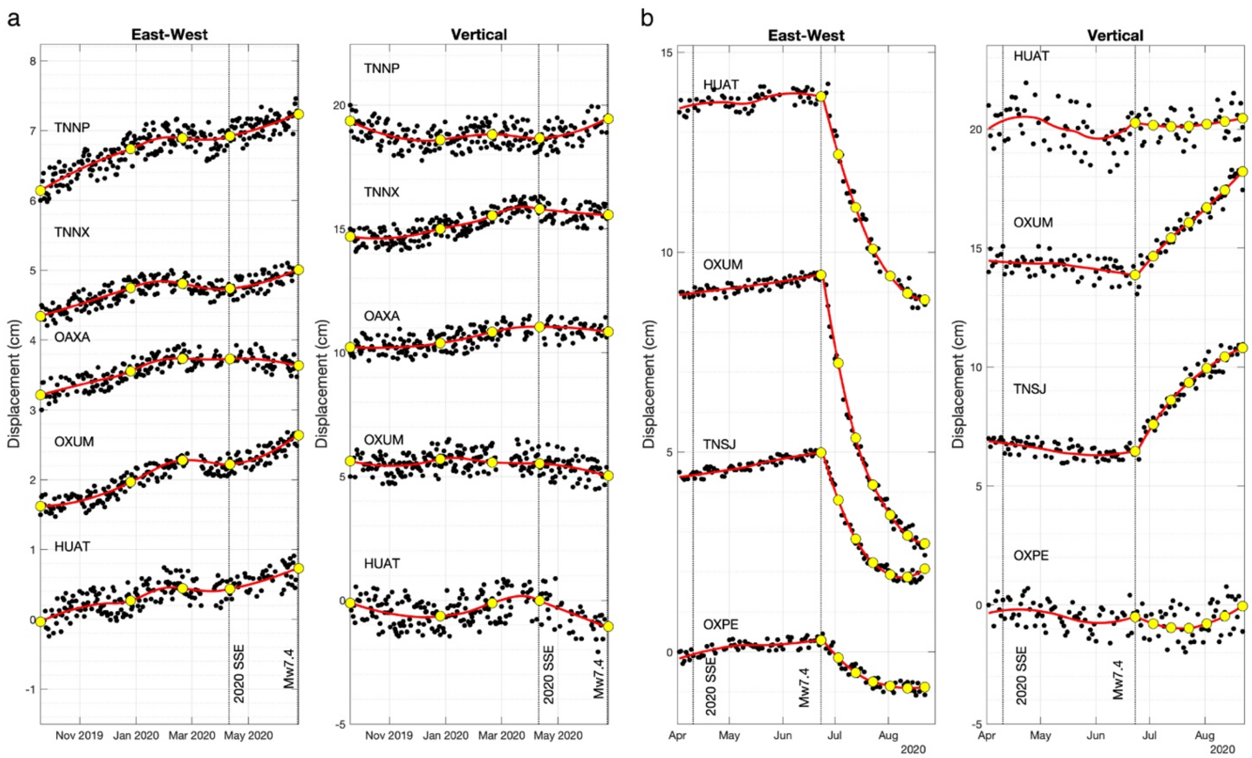

Fig. S6 East-west and vertical GPS displacement time series estimated with the Gipsy-Oasis software for the pre-seismic and post-seismic periods in selected stations shown in figures 2 and 3.

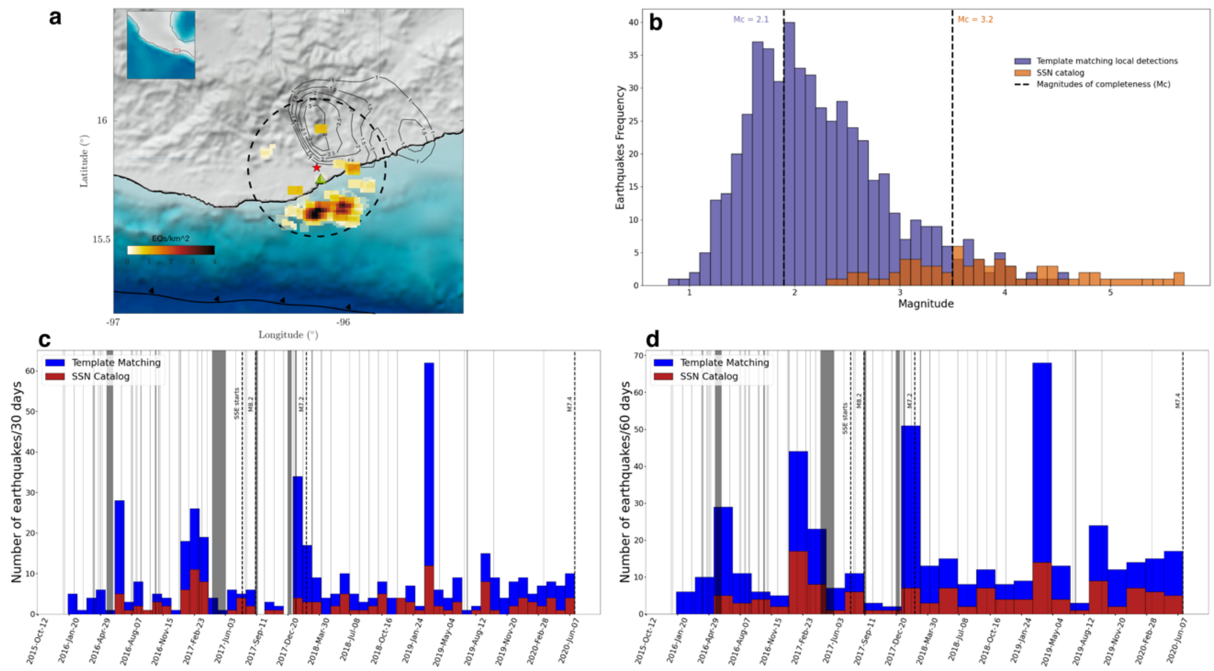

Fig S7 Illustration of template matching (TM) results using the one station method (Cruz-Atienza et al., 2020). **a** Density map of precursor TM detections using the closest station HUIG (green triangle) within 30 km from the Huatulco earthquake hypocenter (red star) and M > 2.1. Notice how almost all the detections are concentrated updip of the hypocenter due to the scarcity of templates located in the Huatulco rupture area. **b** Frequency distributions for the TM and SSN catalogs and their associated magnitude of completeness. **c,d** Seismicity rate evolution for the TM and SSN for two different earthquake rates. Gray sections indicate data gaps.

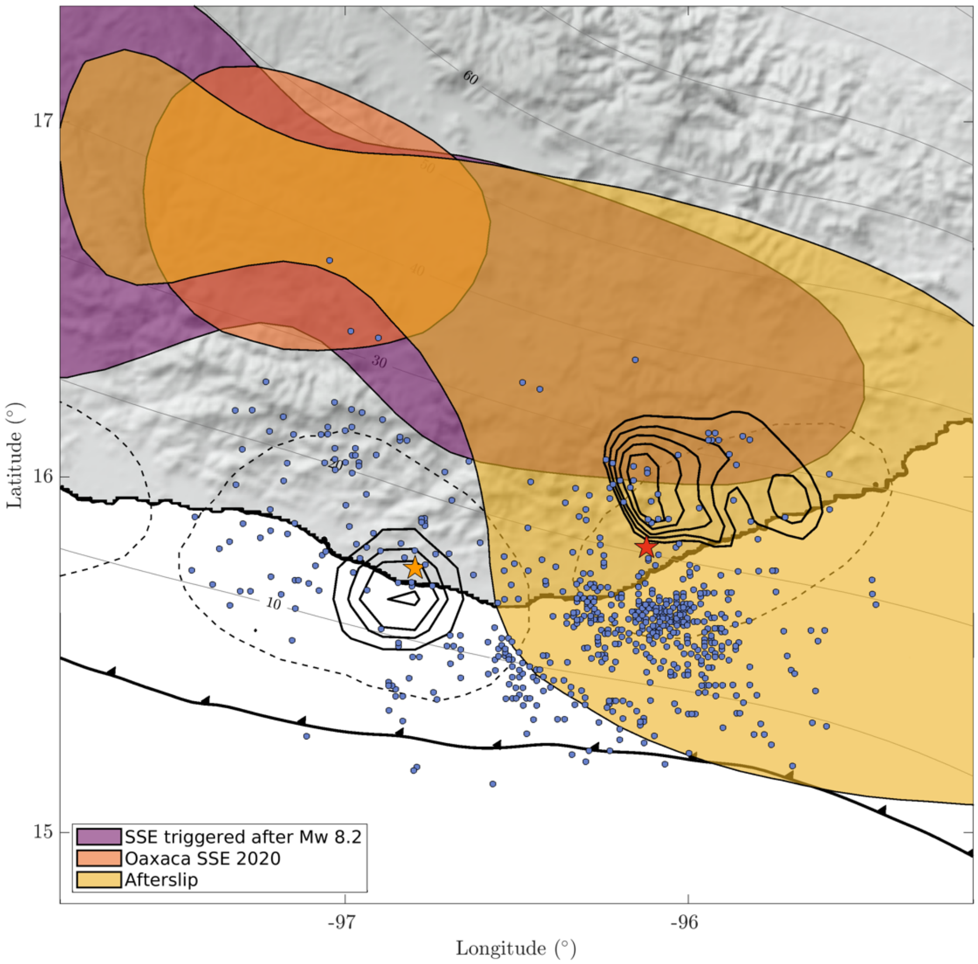

Fig. S8. Comparison of the 2017 SSE area (Cruz-Atienza et al., 2020), the coseismic slip distributions of the 2020 Huatulco (red star) and 1978 Puerto Escondido (orange star) earthquakes (black contours), the two months afterslip area following the Huatulco earthquake and the associated aftershock distribution (blue dots).

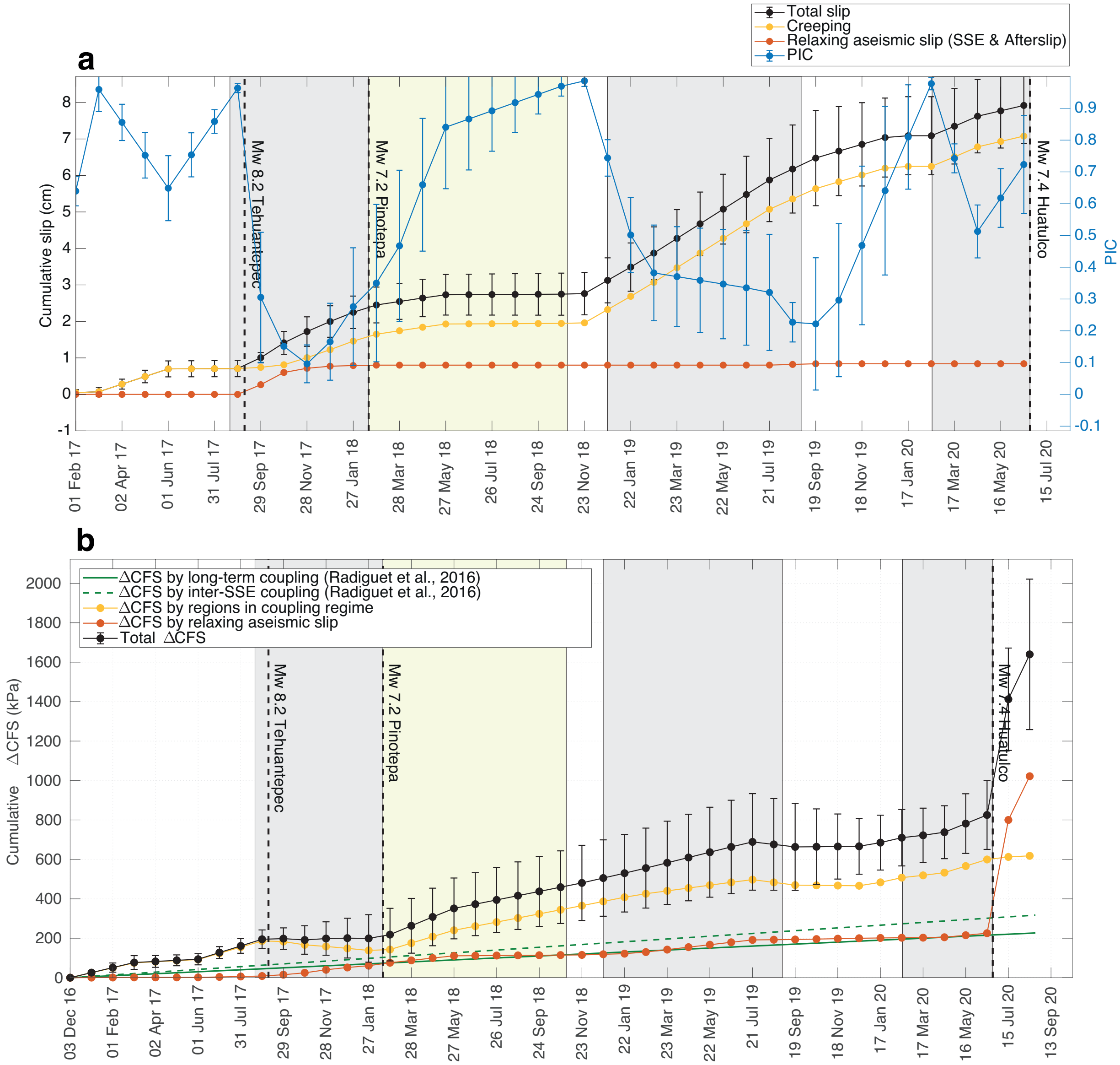

Fig. S9 Evolution of different mean quantities in Region D downdip of the 1978 rupture area (Fig. 4). **a** Cumulative total slip, creeping, relaxing aseismic slip and plate interface coupling; and **b** the total CFS and its components from relaxing slip and coupled interface regions. See Figs. 6 and 9.

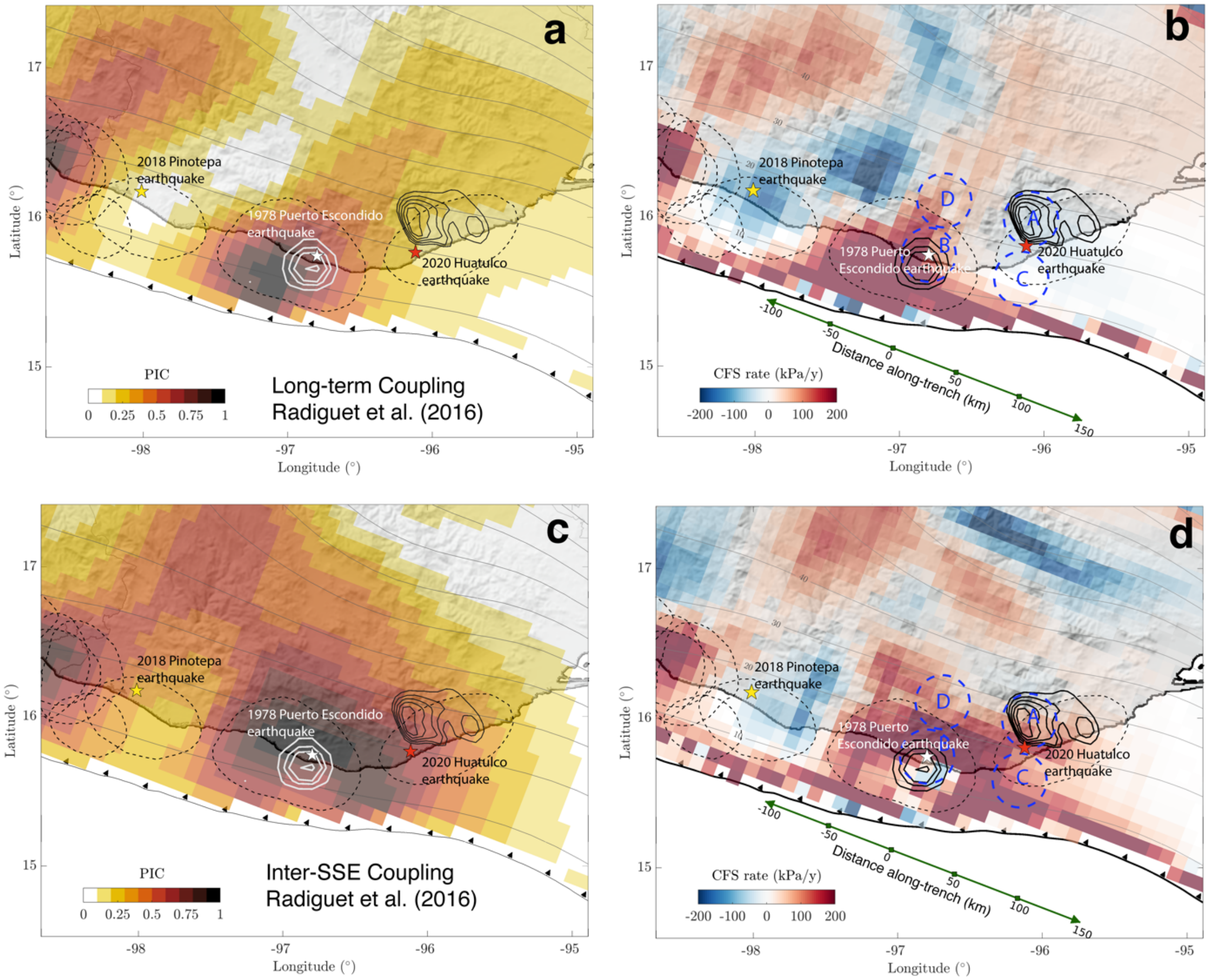

Fig. S10 Long-term and inter-SSE time-invariant interplate coupling models estimated by Radiguet et al. (2016) for the Oaxaca subduction zone and their associated CFS rates.

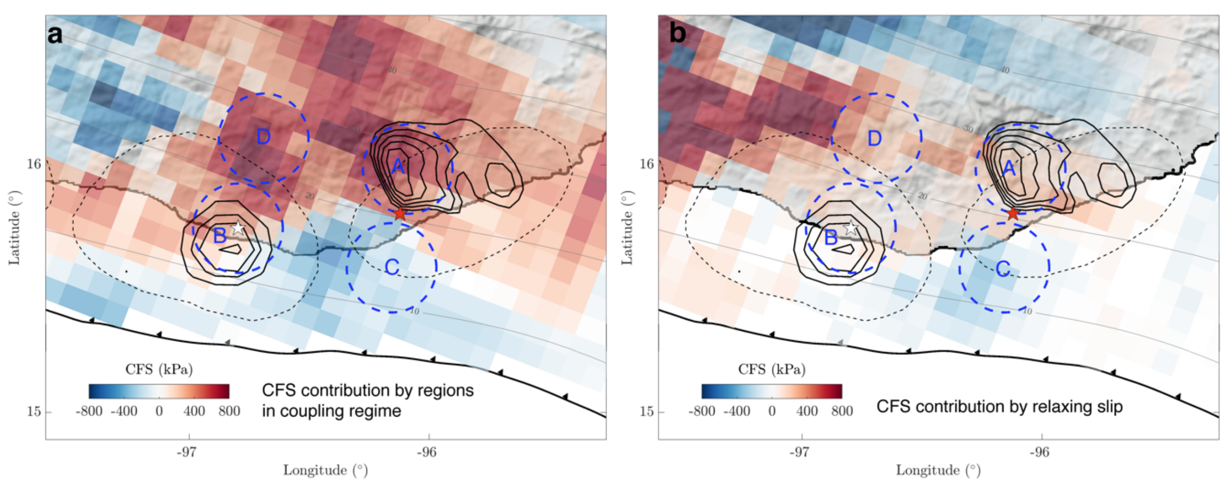

Fig. S11 Cumulative CFS contributions in the plate interface between December 2017 and the date of the 2020 Huatulco earthquake associated with regions in coupling regime (**a**) and relaxing slip (**b**).

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