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Lateral variations of the Guerrero–Oaxaca subduction zone (Mexico) derived from weak seismicity ($M_b 3.5+$) detected on a single array at teleseismic distance

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SUMMARY

Detections of pP and sP phase arrivals (the so-called depth phases) at teleseismic distance provide one of the best ways to estimate earthquake focal depth, as the P – pP and the P – sP delays are strongly dependent on the depth. Based on a new processing workflow and using a single seismic array at teleseismic distance, we can estimate the depth of clusters of small events down to magnitude M_b 3.5. Our method provides a direct view of the relative variations of the seismicity depth from an active area. This study focuses on the application of this new methodology to study the lateral variations of the Guerrero subduction zone (Mexico) using the Eielson seismic array in Alaska (USA). After denoising the signals, 1232 M_b 3.5 + events were detected, with clear P , pP , sP and PcP arrivals. A high-resolution view of the lateral variations of the depth of the seismicity of the Guerrero–Oaxaca area is thus obtained. The seismicity is shown to be mainly clustered along the interface, coherently following the geometry of the plate as constrained by the receiver-function analysis along the Meso America Subduction Experiment profile. From this study, the hypothesis of tears on the western part of Guerrero and the eastern part of Oaxaca are strongly confirmed by dramatic lateral changes in the depth of the earthquake clusters. The presence of these two tears might explain the observed lateral variations in seismicity, which is correlated with the boundaries of the slow slip events.

Key words: North America; Time-series analysis; Body waves; Earthquake source observations; Seismicity and tectonics.

1 INTRODUCTION

We develop a new processing workflow based on a single seismic array, to enhance the detection of depth phases for clusters of events as small as M_b 3.5 detected at teleseismic distances. Our approach is aimed at constraining the mean depth of the seismicity on the case study of the Guerrero–Oaxaca subduction area (GOSA) in Mexico.

A part of this paper discusses the particular application of the method to image the geometry of the GOSA, and in particular its lateral variation along the trench. At this plate boundary, the Cocos plate is subducted under the North America plate (Fig. 1). This zone is especially known for the lack of large earthquakes (Guerrero Gap) in the recent years and the series of slow slip events (SSEs) for both Oaxaca and Guerrero. Knowledge of the lateral variation of this zone would be helpful to better understand its properties. To characterize the Guerrero SSEs, Radiguet *et al.* (2012, 2016) used

global positioning system time-series and relied on the plate geometry derived from receiver-function studies (such as Perez-Campos *et al.* 2008) using data from the Meso America Subduction Experiment (MASE). They show that the SSEs are mainly concentrated inside the Guerrero Gap. In the Oaxaca area, the SSEs have smaller moment magnitudes than in Guerrero (Correa-Mora *et al.* 2008; Graham *et al.* 2016). Understanding the reasons for the extent of these SSEs in Guerrero and Oaxaca is crucial to better understand their mechanisms and differences. The slab geometry might be a good candidate to explain their extents.

Most of the information on slab geometry is derived from earthquake hypocentre locations (Wadati 1935). For the GOSA, such hypocentre locations suggest that the subduction interface between the Cocos and North America plates is relatively flat along the receiver-function line (Pardo & Suarez 1995; Pacheco & Singh 2010). This is shown in Fig. 1, at around 100 km inland from the coast, and after the 40 km isoline. Our knowledge of the geometry

Figure 1. Tectonic map of the Guerrero/Oaxaca subduction zone. Solid grey lines show the depth of the interface of the subducting plate, according to Perez-Campos *et al.* (2008). Large slow slip events are shown with light pink patches (from Correa-Mora *et al.* 2008; Radiguet *et al.* 2012; Graham 2013; Graham *et al.* 2014). Black dashed lines delineate the trench. The white line shows the approximative position of the MASE profile. Line A is the 0 km reference line, positive eastward, used in this study to define lateral distances along the trench (almost parallel to the MASE profile). Line B is the 0 km reference line used to define distances from the trench. The red box is the position of the Guerrero Gap. Coloured lines are cross-sections referred to later in the text. The colorbar corresponds to the mean depth of the seismicity along these cross-sections.

of the Oaxaca subduction area is, however, relatively poor since little seismicity has been recorded there.

High-resolution images of the subduction interface are also available from receiver-function studies performed using data from the MASE (Perez-Campos *et al.* 2008; Song *et al.* 2009). These images confirm the flattening of the subduction for Guerrero, at a depth of around 40 km (e.g. Song *et al.* 2009), and reveal a thin low-velocity zone between the lower continental crust and the slab, which is likely to be an altered oceanic crust or a mantle wedge remnant. However, the receiver-function analysis approach only constrains the image along the receiver line (see Fig. 1). To better understand the occurrence of the SSEs in relation to the characteristics of the subduction zone, an image of the lateral variations of the subduction zone is needed.

In this study, the lateral variations of the GOSA interface are explored. We base our imaging methodology on the hypocentre location, and improve the depth estimations to obtain a better model of the subduction. In general, different methods can be used to improve depth estimation, such as:

- (1) Improvement of the velocity model and localization procedure to relocate the seismicity at a regional distance (e.g. Myers *et al.* 2010).
- (2) Selection of reliable depth estimations from empirical criteria, such as epicentral distance and/or azimuthal coverage at a regional distance (e.g. Pacheco & Singh 2010).
- (3) Detection of depth phases at teleseismic distances (e.g. Engdahl *et al.* 1998).

Regional relocations (method 1) still have important uncertainties due to the trade-off between depth and origin time, lateral changes in the velocity model and a lack of stations close to the source.

Reliable depth estimations extracted from Pacheco & Singh (2010, method 2) and Letort *et al.* (2015, method 3) do not provide a sufficiently dense sampling of the Guerrero subduction zone (~ 200 events) to obtain a precise image of the GOSA. This motivates a new and improved study of teleseismic depth estimations for a higher number of events (i.e. smaller magnitude).

Teleseismic depth estimation relies on correct picking and identification of depth phases. Generally, this can be accessed from the redundancy and coherence of depth-phase arrivals detected from a sufficiently high number of stations with different azimuths (Engdahl *et al.* 1998; Bondár *et al.* 2004; Letort *et al.* 2014, 2015, 2016). Unfortunately, teleseismic P waves are only detected for $M_b > 4$ events (and often only for higher magnitudes), as the signal-to-noise ratio (SNR) is usually weak (< 1) for weaker events. Depth estimation of all $M_b > 4$ events, which represent a set of hundreds of events, would provide a too sparse sampling of the area. Considering the Gutenberg–Richter Law (Gutenberg & Richter 1954), the sampling is likely to be much denser (going from hundreds to thousands of events) if teleseismic depths for $M_b > 3.5$ events can be estimated.

Low-magnitude events ($M_b < 4$) can rarely be detected at teleseismic distances, and usually only a few stations, if any, can be used. For instance, Letort *et al.* (2014) observed clear teleseismic P , pP and sP phases with high SNR (> 3) from an earthquake of M_L 3.6 (Ardeche, France), which were recorded using the FINNES single array in Finland. However, no other P -wave arrivals were detected at any of the other stations/arrays throughout the whole set of stations/arrays available at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center, and at the Comprehensive Nuclear Test Ban Treaty Organization Data Center. For these reasons, the redundancy of coherent detection among

different stations can no longer be used to characterize the depth of low-magnitude earthquakes ($M_b < 4-4.5$).

In this study, we investigate the possibility to use a single small aperture array at teleseismic distance to address this problem. As the phase arrivals from one single event can be difficult to interpret as pP or sP , and could be due to other unknown reflections, we interpret these phase arrivals from, not only one but clusters of events along a cross-section. We therefore use the redundancy and progressive variations of coherent phase arrivals from tens to hundreds of earthquakes in the same area, instead of using the redundancy of phase arrival detections from one event among stations in different azimuths, as is commonly done (e.g. Bondár and Storchak, 2011).

The Eielson seismic array (ILAR; Alaska, USA) turned out to be one of the best arrays that constrain the depth estimations of the Guerrero area (from a global teleseismic depth estimation study following Letort *et al.* 2015). ILAR is an AFTAC (Air Force Technical Application Center) array, and is part of the International Monitoring System that is freely available via the International Federation of Digital Seismograph Networks–IRIS web service. The array is on the eastern side of Fairbanks (Alaska, USA), and is ideally located on the North American Craton, at a distance of 55° – 60° from Guerrero. It comprises of 21 stations, including the 19 short-period vertical stations used in this study, with an aperture of ~ 25 km.

From this single array and using a denoising procedure, 1232 recordings for $M_b > 3.5$ events show clear P , pP , sP and PcP arrivals. The high numbers of earthquakes observed from a single array provide a dense sample of the whole GOSA, while the more common approach based on combining teleseismic stations from different azimuths only allows to constrain around 100 events (Letort *et al.* 2015). Hence, the single array approach gives new insights into the lateral variations of the average depth of the seismicity.

2 DEPTH-PHASE IDENTIFICATION USING A SINGLE ARRAY

2.1 Denoising procedure

Successful clear detection of the teleseismic depth phases from events in the GOSA relies on the ability to isolate them from noise and from other teleseismic and regional sources. We thus developed a technique that is based on singular value decomposition, to remove the noise and the other arrivals, and only keep teleseismic arrivals from the GOSA. This filtering is performed in the frequency domain, using a so-called ‘spectral-matrix filtering’.

The principle is to first rely on the regional localizations of the GOSA events and estimate the associated theoretical arrival times (T_p) at ILAR, using the Ak135 global velocity model (Kennett *et al.* 1995). Then, we select 250 s time windows that include all of the P arrivals from the GOSA events (90 s before T_p and 160 s after T_p), even if these appear to be hidden in the noise. All of the events since 2000 in the Guerrero area with magnitude $M_b > 3.5$ are downloaded from the IRIS web service (1232 events). The 250 s recordings are then filtered between 0.5 and 2.5 Hz for each of the 19 short-period stations of the array. These time-series are a mix of ambient noise, signals from regional/local earthquakes and mainly signals from Guerrero–Oaxaca (an example is shown in Fig. 2). The top of the time series (i.e. $> 2 \times$ standard deviation) is cut-off and whitened, and the spectral matrix is estimated using a so-called spatial smoothing (i.e. to make the matrix invertible; such as in Paulus & Mars 2006). The smoothing is applied using

a large moving time window of 20 s, with an overlap of 10 s. Once the spectral matrix has been estimated, we define two vector subspaces for each frequency f : the signal subspace SP_{1-2} generated by the first two eigenvectors associated to the highest eigenvalues and the noise subspace SP_{3-19} which is its complementary subspace. The initial data are then projected onto the signal subspace. Fig. 2 shows the projection onto the signal subspace SP_{1-2} (Fig. 2b) for an example time-series (Fig. 2a). The projected signal clearly enhances the signals from the GOSA, while the noise and regional signals are projected onto SP_{3-19} , the orthogonal subspace (Fig. 2c). All events are thus denoised and stacked using this method; they can be seen in the cross-section in Fig. 3, and are discussed further in the next section.

2.2 Envelope averaging along cross-sections

Fig. 3(a) represents all of the denoised recordings in a cross-section that is perpendicular to the trench and aligned to the P -wave arrivals (at 2 s). On this figure, the wave packet corresponding to the depth phases (i.e. pP and sP) varies continuously between $+5$ s (before and around the trench), to $+25$ s (when reaching 250–300 km away from the trench) after the P -wave arrival. This continuous variation in depth-phase arrival times is a direct view of the deepening of the seismicity, as expected along a subducting plate. A 5 km wide spatial smoothing is then applied to the recording envelopes, to enhance the depth-phase arrivals (Fig. 3c).

The cross-sectional figure therefore allows a direct and completely data-driven view of the 1-D variation in depth of the seismicity along the subduction zone without any prior assumptions. It is interesting to note that the averaging procedure allows to efficiently enhance depth-phase arrivals up to 100 km from the trench. However, for the deeper part of the subduction, we observe a wide temporal range in the depth-phase arrivals package, as earthquakes probably occur in a wider depth range. Note that PcP can be detected only at distances of ~ 130 km from the trench, around ~ 60 s after the P arrival. In Fig. 3(d), when the cross-section is along the trench (line B in Fig. 1), PcP are detected all along the trench: this demonstrates the important role of the orientation of the cross-section for an efficient averaging of coherent phase arrivals.

Different cross-sections have therefore been processed, either perpendicular or parallel to the trench (following the direction of the MASE line and line B; Fig. 1). In Fig. 4, the cross-section parallel to the trench CST1 (Fig. 4a) is obtained by the summation of the envelopes for all of the events between 1.4° (~ 155 km) and 2.2° (245 km) from the trench (Fig. 1, line B) and with a lateral averaging window of 0.5° (~ 56 km). P , pP and sP arrivals are all detected (Fig. 4b) and can be easily picked. Using the Ak135 propagation model (Kennett *et al.* 1995), the time delays between the P and the depth phases can be converted into depths (Fig. 4c). All of the cross-sections analysed are shown in Fig. 5, providing a 3-D high-resolution view of the localization of the seismicity.

2.3 Depth-phase interpretations

For a given cross-section, two scenarios are possible.

(1) Two distinct groups of phase arrivals are detected after the direct P waves as seen when analysing the signals from cross-section CST1 (Fig. 4b), and these are interpreted, respectively, as pP and sP arrivals. The P – pP and the P – sP delays both fit the same depth values, giving a high confidence to the phase interpretations and depth estimations (Fig. 4c).

Figure 2. Illustration of the projection method. (a) Signals observed from the array recordings after filtering between 0.8 and 2.5 Hz. The arrivals from an event in Guerrero (at ~ 90 s) is observed hidden in the noise and in the signals from another event (in the region of the array location) at ~ 190 s. (b) Projection of the recordings in the ‘main direction’ (projection onto the subspace generated by the 2 first eigenvectors, estimated previously from the set of recordings containing several events from Guerrero, see Section 2.1). For the Guerrero event, the P -wave arrivals are better detected and a later depth phase is also detected (assumed here to be a pP phase, see Section 2.3 for the discussion on the depth-phase interpretations). The regional event almost disappears after projection. (c) Projection of the recordings in the orthogonal subspace. The event from Guerrero has been removed, and the regional arrivals are better detected.

(2) However, only one coherent phase arrival pattern is detected after the direct P waves in certain cases, such as between 0 and 100 km from the trench (see cross-sections CS2, Fig. 6 and CS3, Fig. 7). The type of depth phase (pP or sP) then needs to be assumed from independent knowledge. Following Pearce & Rogers (1989), we can predict the predominant depth phase (pP and sP) according to the focal mechanism. According to Pacheco & Singh (2010), the mechanisms are mainly normal in slab or thrust interpolate, until around 80 km from the trench. These are likely to generate high-amplitude sP phases and low-amplitude pP phases for ILAR, as shown by Letort *et al.* (2015). Thus, we interpret that the phase arrivals times seen on CS2 and CS3 are sP arrivals. This interpretation is also validated by a comparison with independent depth estimations and is coherent with the receiver-function analysis along the MASE profile (see Section 2.4).

2.4 Validation of the depth derived from the cross-sections

In order to evaluate the cross-sections, we compare the results to (1) well-constrained local depth estimations (Pacheco & Singh 2010), (2) teleseismic depths estimated from the cepstral method developed by Letort *et al.* (2015), (3) a new teleseismic study after an update of the method (Letort *et al.* 2015) using all stations in the II, IU, AFTAC and Geoscope IRIS networks and investigating all events in the ISC catalogue with $M_b > 4$ and (4) a relocation of all of the seismicity using the new ISC-Locator algorithm (Bondár & Storchak 2011) and a 3-D regional velocity model (Myers *et al.* 2010). A comparison between all approaches is shown in Fig. 5.

Good agreement is obtained between all of the methods for the main features of the subduction.

The shape of the seismicity along the MASE profile is then compared to the geometry proposed by Radiguet *et al.* (2012). This geometry was derived from the receiver-function analysis, and is similar to the geometry proposed by Perez-Campos *et al.* (2008). We compare this 1-D geometry for the two cross-sections on either side of the MASE profile (CS2 on the western side and CS3 on the eastern side).

(1) On the western side of the MASE profile (Fig. 6), in the Guerrero Gap, the seismicity derived from the cross-section follows the shape of the receiver-function profile. As light bias between these two profiles can be observed. This difference can be easily explained by differences in the velocity model and the precision of the picking of the depth-phases and/or the reflection interface for the receiver function. Moreover, the cross-section is a representation of the depth of the seismicity, and not a direct view of the interface: intraplate events might be deeper than the interface, as shown by the study of the focal mechanisms (Pacheco & Singh 2010).

(2) On the eastern side (Fig. 7), the profiles compared are different at around 50–100 km from the trench, where the cross-section profile reaches a high dipping angle. This feature is not observed for the receiver-function profile, or on the Pacheco & Singh (2010) interface. As Pacheco & Singh (2010) found crustal events east of the Guerrero Gap, and only few inside the gap, their cross-sections may not be a direct view of the interface, but could reflect the mean crustal seismicity (see the next section).

Figure 3. (a) Application of the denoising method for all of the events and the stack of the stations of the array. The final stacked signals are normalized, aligned according to the *P*-wave arrival time, and represented and sorted according to their distance to the trench. Note the clear trend of the depth-phase arrivals, which arrive ~ 5 s after the *P* for events located close to the trench, and then later when moving further away from the trench. (b) Map of all events used for this study. The colour is the depth estimation value in the ISC catalogue. (c) Averaging of the signal envelopes seen in (a), for an averaging moving window of 0.05° . (d) Same as (c), but for a cross-section parallel to the trench, and an averaging moving window of 0.1° .

Figure 4. (a) Events used for cross-section CST1 (see Figs 1 and 5), at an average distance of 192 km from the trench. (b) Cross-section of envelopes from the events in (a), showing the *P*, *pP*, *sP* and *PcP* arrivals. (c) Picking of the *pP*/*sP* arrivals seen in (b), and the associated depth profile.

Figure 5. Comparison of the average depth profiles derived from the cross-sections (obtained in this study) with trustable punctual depth estimations (cepstral teleseismic depths and local depths from regional relocation) and with the average seismicity from the ISC-Loc/Regional Seismic Travel Time inversion procedure. The red arrow indicates the position of the Orozco fracture zone (OFZ).

Figure 6. (a) Events used for cross-section CS2 (see Figs 1 and 5), west of the MASE profile. (b) Cross-section of envelopes from the events in (a), showing the P , pP and sP arrivals. The black and red lines are the positions of the pP and sP arrivals respectively, from the theoretical events located exactly at the interface, as used by Radiguet *et al.* (2012). (c) Picking of the pP/sP arrivals seen in (b), and associated depth profile.

Figure 7. (a) Events used for cross-section CS3 (see Figs 1 and 5), east of the MASE profile. (b) Cross-section of the envelopes from events in (a), showing the P , pP and sP arrivals. The black and red lines are the positions of the pP and sP arrivals, respectively, from the theoretical events located exactly at the interface, as used by Radiguet *et al.* (2012). (c) Picking of the pP/sP arrivals seen in (b), and the associated depth profile.

Figure 8. (a) Position of the events used for cross-sections CSA (yellow), CSB (red), CS1 (blue) and CS2 (black), as described in Fig. 5. (b) Proposed profile of the interface seismicity for these three cross-sections from (a). (c)–(f) Cross-sections of the averages of the envelopes of the teleseismic recordings, as observed for (c) CSA, (d) CSB, (e) CS1 and (f) CS2. The P (at ~ 2 s), pP (orange) and sP phases (black) are clearly detected by the high amplitudes (yellow) and are indicated by the dashed lines. Some arrivals cannot be attributed to interface events (circles), and these are assumed to be related to crustal events or due to incorrect epicentral localization. (f) The Guerrero Gap location corresponds to CS2.

Figure 9. Cross-sections parallel to the trench (CST) described in Fig. 5, showing the average of the envelopes of the teleseismic recordings, from -600 to 400 km with respect to line A (Fig. 6). (a)–(d) Cross-sections CST4 to CST1 are 74 , 94 , 118 and 192 km, from the trench, respectively. The P (~ 2 s), pP , sP and PcP phases are clearly detected by the high amplitudes (yellow). The interpretations of the pP , sP and PcP arrivals are shown by the orange, black, and brown dashed lines, respectively.

These comparisons appear to indicate that the shape of the seismicity is mainly following the interface geometry, as there are few differences between the receiver-function and cross-section profiles. The seismicity is then a good indicator of the position of the interface, and can be used to discuss the lateral variation of the GOSA in the next section, keeping in mind that the presence of crustal seismicity may bias the results.

2.5 Possible epistemic uncertainties

The approach developed in this study, using only teleseismic data, aims to improve depth estimation, the most difficult parameter to constrain during localization procedures (Bondár & Storchak 2011). However, it is assumed that epicentral localizations are correct in the catalogue. In cases of small (less than 20 – 30 km) or a low number of epicentral localization errors, the envelope averaging procedure, with an averaging moving window of 0.5° , should greatly reduce possible the bias that could come from these errors on the estimated depth profiles. Only for an important number of large epicentral localization errors for a same cross-section (>30 km), the estimated depth profiles could be a biased representation of the seismicity. This could occur when there are important gaps in the azimuthal station coverage (see Bondár & Storchak 2011).

Another possible bias could come from events located under the sea layer. The observed reflected waves would then be pwP/swP instead of pP/sP . In case of a misinterpretation of pwP/swP phases, the estimated depth values could be overestimated between 0 and 40 – 50 km with respect to the trench (the coast is approximately at 50 km). However, this possible bias would have no influence on the

lateral variations of the seismicity observed and discussed in the next section, which appear further away from the coast.

3 LOCALIZATION OF THE SEISMICITY, GEOMETRY OF THE PLATE AND IMPLICATION FOR UNDERSTANDING THE SLOW SLIP EVENTS

3.1 Lateral variation of the shallow seismicity correlated to the position of the Guerrero Gap

We first focus on the shallower part of the subduction, from 0 to 100 km from the trench for cross-sections perpendicular to the trench CSA–CSB and CS1–CS2 (Fig. 8). The time arrivals of the depth phases (assumed to be mainly sP , see previous section) are strongly different according to the cross-sections, related to the variation in depth of seismicity at the western rim of the SSE (Figs 9c–f between CSA–CSB and CS1, CS2). The seismicity appears to be widely dispersed at different depths for CSB, appears to remain constant for CS1, and appears to be constantly dipping with a low angle in the SSE area (CS2, Fig. 8). This difference can be explained by:

(1) The presence of crustal normal faults above the subduction on the western rim of the Guerrero Gap. If there is a mix of crustal and interface earthquakes in the same area, the depth phases are not representative of the depth of the plate interface, but of the depth of the crustal seismicity, or they might even correspond to an average depth between the crustal and interface seismicity (i.e. mixing of pP/sP phases). The larger pattern of the depth-phase arrivals that is observed for CSB (Fig. 8d) and at ~ 70 – 100 km for CS1 (Fig. 8e) at

Figure 10. (a) Position of cross-sections CS6 (green), CS7 (red) and CS8 (black). (b) Proposed profile of the interface seismicity for these three cross-sections. (c)–(e) Cross-sections of the average of the envelopes of the teleseismic recordings observed, for (c) CS6, (d) CS7 and (e) CS8. The P (~ 2 s), pP (orange) and sP phases (black) are clearly detected by the high amplitudes (yellow) and indicated by the dashed lines. (d) The Oaxaca SSE gap is located along CS7.

the border of the gap might then be a clue to the presence of a mix of shallower crustal and deeper interface events, while only interface events occur inside Guerrero Gap (Fig. 8f). Under this hypothesis, crustal events occur on both sides of the Guerrero Gap, but not within, which may indicate that the crustal faults control the extent of Guerrero Gap.

(2) A dramatic change in the geometry of the subducting plate around CSB and CS1. On CSB, the large pattern of the depth-phase arrivals (Fig. 8d) is probably a mix of crustal and interface events, making it difficult to clearly identify depth-phase arrivals due to interface earthquakes. However, the presence of a deep seismicity around 30–50 km from the trench (i.e. later phase arrivals at 20–25 s, Fig. 8d) could be due to the interface (with a crustal seismicity above). From this hypothesis, the interface is clearly deeper in CSB than in CS1 where the tight clustering of the seismicity observed in the cross-sections (Fig. 8e) is assumed to follow the interface. This sharp variation between CSB and CS1 is interestingly correlated with the presence of the Orozco fracture zone (OFZ, see the next section).

3.2 Influence of the Orozco fracture zone fault and a possible tear at the western rim of the SSE

The OFZ fault is located at the western part of Guerrero (Fig. 8, CSB). There is an ultra-slow velocity layer at the top of the subducting Cocos plate (Song *et al.* 2009; Dougherty *et al.* 2012) that ends on the western margin of the OFZ, and which might be consistent with the interpretation of a tear in the Cocos plate around this margin, first proposed by Bandy *et al.* (2000) and later asserted by Dougherty *et al.* (2012) and Stubailo *et al.* (2012). In the previous section, we showed important depth variations between CSB and CS1 (Figs 8d and e), at the OFZ, around 30–50 km from the trench, although there is less lateral variation when further than 190 km from the trench (Fig. 4). In the light of these previous stud-

ies, the observed sharp variation between the two cross-sections is a confirmation of a possible tearing in this area.

3.3 Deeper events in Oaxaca and/or the tear of the plate

All of the methods shown in Fig. 5 indicate deeper seismicity for the Oaxaca region (>60 km) compared to the Guerrero region (<60 km). This clear change in focal depth was previously observed by Dougherty & Clayton (2014). They also noted a sharp transition in slab dip and the presence of the boundary of the low-velocity zone, at the east of line A (Fig. 5). They propose that these features could be caused by a tear in the plate. The lack of seismicity between Oaxaca and Guerrero around line A (Fig. 5) supports the hypothesis of a slab tear, as the apparent absence of slab seismicity is an important clue for a slab window opening, according to several studies (Guillaume *et al.* 2010; Johnston & Thorkelson 1997; Ferrari 2004; Levin *et al.* 2005).

When looking at cross-sections perpendicular to the trench, there is a dramatic change in the seismicity east of the Oaxaca SSE (Fig. 10). This is in agreement with Dougherty & Clayton (2014), who reported a greater dip angle for this area. This change might be partially due to a change in the trench geometry. However, the difference in curvature of the seismicity profile (from 100 to 150 km from the trench; Fig. 10b) is more likely to be evidence of the tearing of the plate (at ~ 100 km from the trench), exactly at this eastern part of the Oaxaca SSEs. In Fig. 11, the proposed geometry of the interface allows the explanation of all of the previously described lateral changes seen for the seismicity:

- (1) The tearing of the plate at the east of the Oaxaca region explains the absence of seismicity.
- (2) The presence of two tears at 100 km from the trench in Oaxaca but only a few kilometres from the trench in Guerrero explains the observation of the lateral changes in the dip of the plate (the

Figure 11. Schematic view (not to scale) of the Guerrero–Oaxaca plate interface. The SSEs are represented by the brown contours; the isolines by the black dashed lines; and the main cross-sections (see Figs 1 and 5) are indicated by the red dashed lines.

seismicity becomes deeper in Guerrero, but remains shallower in Oaxaca, until 100 km from the trench).

(3) The two tears can be directly related to the observation of the extent of the SSEs: the Guerrero SSEs are limited at the west by the tear in the prolongation of the Orozco fracture zone, while the Oaxaca SSEs are limited by the Oaxaca tear at the east.

(4) The ultra-slow velocity layer described by Song *et al.* (2009) and extended to the east by Dougherty & Clayton (2014) coincides perfectly with the observed flat area of the Guerrero–Oaxaca subduction.

4 CONCLUSIONS

We have developed a new approach to evaluate depth variations of subduction earthquakes concentrated along an interface. From one unique teleseismic array and using a denoising procedure based on an eigenvector subspace decomposition to enhance depth-phase arrivals, we can provide information about the lateral changes of the weak seismicity down to M_b 3.5. We thus obtain a high-resolution map of the depth of the seismicity. This method can be applied to other subduction zones and other tectonic contexts.

The application of this method to the GOSA reveals that the lateral variations in depth estimations are relatively small in this region, in terms of possible variations due to lateral velocity changes that can affect depth-phase arrivals. However, this original and innovative method allows a direct view of the shape of the seismicity distribution. The results are obtained in a completely data-driven way, without any modelizations and/or inversion processes which could bring epistemic uncertainties. This method shows different tendencies for the curvature and slope of the seismicity for the different cross-sections, which are especially strong evidence for a tearing of the plate at Oaxaca. On the western part of the Guerrero gap, there is less obvious evidence of another tearing, or at least a dramatic change in the lateral shallow crustal faulting system, which is correlated with the presence of the Orozco fracture zone.

This qualitative information on the geometry provides new insight into this area, and deeply strengthens the hypothesis of the double tear of the plate proposed by Dougherty & Clayton (2014). These two tears explain the observed properties of the seismicity. Furthermore, these results show that the extent of the SSEs seem to be delimited by the two tears. Hence, plate geometry variations, but also a possible mantle flow between the segments allowed by the presence of the tears, could play a role in the presence and the extent of the SSEs.

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