



Path-specific, dispersion-based velocity models and moment tensors of moderate events recorded at few distant stations: Examples from Brazil and Greece

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ABSTRACT

Centroid moment tensor (CMT) determination in intraplate regions like Brazil can be very difficult, because earthquakes are often recorded just at few and distant stations. This paper introduces a methodology for datasets like that. The methodology is based on waveform inversion in which each source-station path has its own velocity model. The 1-D path-specific velocity models are derived from the Rayleigh- and Love-wave dispersion curves. The waveform inversion is accompanied by posterior check of numerous P-wave first-motion polarities. An important innovation is the use of so-called frequency range test. The test basically consists in calculating CMT's for many different frequency ranges to assess the stability and uncertainty of the solution. The method is validated on two Brazilian earthquakes and a well-known Greek event. An offshore event (mb 5.2) in SE Brazil is inverted with four stations, at epicentral distances 300–400 km. The other Brazilian earthquake (mb 4.8 in Central Brazil) is even more challenging – only two broadband stations at 800–1300 km are at disposal for waveform inversion. The paper unambiguously demonstrates that the path-specific velocity models significantly increase the reliability of the CMT's. While standard models (e.g. IASP91) typically allow waveform modeling up to epicentral distances of the order of a few (–10) minimum shear wavelengths (MSW), using the path-specific velocity models we successfully inverted waveforms up to > 20 MSW. Single-station waveform inversions are thoroughly tested, but multi-station joint inversions are shown to be preferable. The new methodology of this paper, providing a reasonable estimate of focal mechanisms and their uncertainties in case of highly limited waveform data, may find broad applicability in Brazil and elsewhere.

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1. Introduction

The moment tensor solution is an important tool to understand earthquakes. It provides a simple point-source rupture model, characterized by centroid position and time, nodal planes (strike, dip, and rake) and moment magnitude (M_w). These data are essential for other research fields such as seismic hazard assessment (Convertito and Herrero, 2004; Morrato et al., 2007) and seismotectonic studies (Presti et al., 2013; Herman et al., 2014).

In areas with few earthquakes and sparse station distribution, many events are recorded only at large epicentral distances, which complicates determination of the moment tensor. In particular, in

the intraplate areas, where seismic attenuation is low (Hwang et al., 2011; Barros et al., 2011), earthquakes of moderate magnitudes can be well recorded up to distances ~ 1000 km. However, the determination of moment tensor at large regional distances can suffer from inherent inaccuracy of the velocity model (e.g., Nayak and Dreger, 2014). A particular challenge is the moment tensor determination from a single station (Fan and Wallace, 1991; Dreger and Helmberger, 1993; and Kim and Kraeva, 1999).

In this work, we discuss the importance of 1-D velocity models specifically derived for each source-station path. We show, similarly to Assumpção et al. (2011) and Herrmann et al. (2011), that using surface-wave group-velocity dispersion inverted into 1-D velocity models for each source-station path can significantly improve the reliability of the moment tensor (MT) determination. We also present a new tool to check the stability of the MT solution: the frequency range test. It consists of performing the waveform

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inversion for many different frequency ranges and systematically investigating variation of the MT solution and its quality. The solution quality is characterized by waveform fit (quantified by variance reduction). The P-wave first-motion polarities are used as additional information to constrain the solution. As such, not only the best-fitting MT solution is calculated, but also a group of solutions well-fitting the data is identified, providing information about the focal-mechanism uncertainty.

We illustrate the methods on the focal mechanism determination of two recent moderate-size earthquakes (mb 5.2 and 4.8) in Brazil that were recorded only at few (2–4) regional stations. Furthermore, we test our methodology also on one earthquake with well-determined focal mechanism in the western Corinth Gulf in Greece. As a special case, single-station inversions are also discussed.

2. Methods

2.1. Surface wave analyses

We build a 1D velocity model using the Love- and Rayleigh-wave group velocity dispersion along each source-station path to calculate the Green's function for the waveform inversion following the steps below:

1. Rotation of horizontal components into transversal component.
2. Measure of the Rayleigh and Love surface waves group velocity dispersion in the vertical and in the transversal components, respectively.
3. Creation of more than 3000 initial velocity models with different criteria to execute the inversion.
4. Inversion of the surface wave velocity dispersion into final shear velocity model.
5. Selection of the best models according to their misfit and construction of a weighted mean to be used for the waveform inversion.

We analyze the group velocities with multiple filtering techniques using the codes of Herrmann (2013). The Rayleigh and Love wave dispersion is measured on the vertical and transverse component, respectively. We use records providing clear and unambiguous dispersion curves in a period range at least 10 s long, in both components. Moreover, we also require that at least one component must provide the dispersion curve for periods higher than 30 s.

The inversion of the dispersion curve into shear velocity models is made using methodology of Julià et al. (2000). The code uses damped least-square method; it allows for weighting the initial velocity of each layer and controlling the smoothness of the velocity variation between layers. Initial models of four different patterns are created in the present paper:

- a) Models with constant-velocity layers of equal thickness;
- b) Models with constant-velocity layers whose thickness increases with depth;
- c) Models as (a), but with Moho depth prescribed with a large weight (almost fixed);
- d) Models as (b), but with Moho depth prescribed with a large weight (almost fixed).

In the creation of the initial models following the patterns c) and d) we utilized information about Moho depth given by Assumpção et al. (2013). The authors compiled data on crustal thickness studies in South America from receiver function, surface wave analysis and deep seismic refraction. In our initial models, the layer

corresponding to Moho has a weight of 10 while other layers have weight 1. Additionally, several different smoothness constraints are applied. All together, we create more than 3000 initial models for each path.

The misfit between the observed (d) and synthetic (s) dispersion curves is defined as follows:

$$M = \frac{W_R \sum \frac{(d_R - s_R)^2}{d_R^2} + W_L \sum \frac{(d_L - s_L)^2}{d_L^2}}{W_R + W_L} \quad (1)$$

where the subscript R and L denotes the Rayleigh and Love waves and W_R and W_L are their weights. The inversion of dispersion curves is performed for each initial model and the fit is measured according Equation (1) discarding the final inverted models with two or more velocity inversions (by velocity inversion we mean a local decrease of velocity with depth). To define velocity models for the waveform inversion, we calculate the weighted mean of the final models whose misfit is between the obtained minimum and some setup maximum. Here we choose the maximum equal 3*minimum. The weights are given by $1/M$.

The inversion of dispersion curves is made for the S-wave velocity, V_s , while the V_p velocities are derived using an assumed V_p/V_s ratio, constant with depth. An example of the dispersion-curve inversion is shown in Fig. 1. The spectrogram used to derive the dispersion curve, i.e., the period versus group velocity diagram, is shown in Fig. S1 (electronic supplement).

2.2. Moment tensor solution

We use ISOLA (Sokos and Zahradník, 2008, 2013) to invert full 3-component waveforms into the centroid moment tensor. The code calculates Green's functions by the discrete wavenumber method (Bouchon, 1981; Coutant, 1989). The deviatoric moment tensor is calculated by least-squares fitting of the observed and synthetic seismograms, while the centroid time and depth are grid-searched. The resolvability of the inversion is quantified by condition number (CN): low values, about 2–5, imply that the moment-tensor is relatively well resolved, while large values indicate an ill-posed problem whose solution may have no physical meaning. In our tests, we perform the waveform inversion for stations weighted equal to their epicentral distance, accompanied by a posterior check of first-motion polarity agreement. The waveform fit is quantified by the weighted variance reduction VR (≤ 1):

$$VR = 1 - \frac{\sum W^2 (d - s)^2}{\sum W^2 d^2} \quad (2)$$

where d and s are the observed and synthetic seismograms, respectively, and W is the weight (equal to the station epicentral distance).

2.3. Frequency range test

The moment tensor solution needs a suitable frequency range. The low-frequency cutoff limit is given by the signal-to-noise ratio, while the high-frequency limit depends on the quality of the velocity model (e.g. Fojtíková and Zahradník, 2014; Zahradník et al., 2015). Standard velocity models, for example those used to locate earthquakes, typically enable waveform modeling only at wavelengths greater than 1/10 of the epicentral distance (Zahradník et al., 2015). Specific path-dependent models may increase the standard high-frequency cutoff, and we investigate such a possibility. That is why in this paper we repeat the waveform inversion in several frequency ranges, trying to define the (possibly multiple)

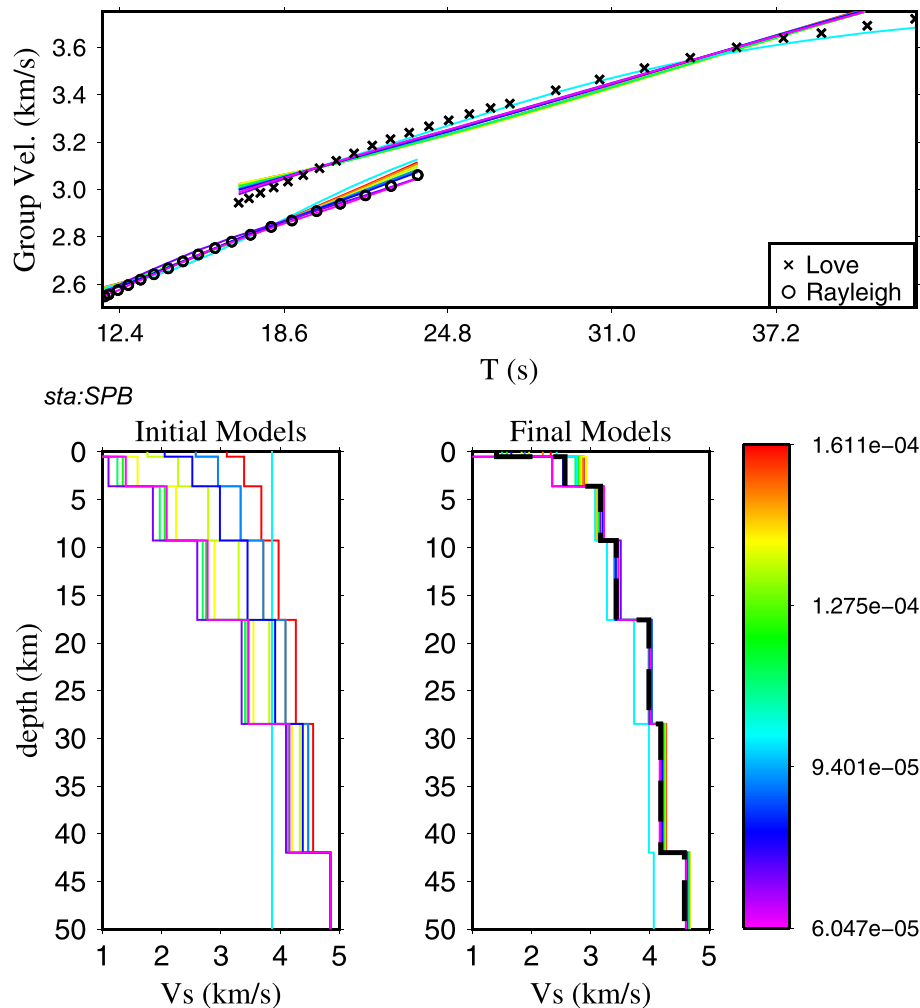


Fig. 1. Inversion of surface wave dispersion for the Offshore event at SPB station (epicentral distance ~300 km). **Top:** the observed group velocity curves for Love and Rayleigh waves (crosses and circles) and synthetic curves for the best fitting models (color lines). At SPB station, we are able to measure periods between 12 and 25 s and 15 and 45 s for Rayleigh and Love waves respectively. **Bottom left:** S-wave velocity profiles of the initial models. **Bottom right:** the final models. The dashed line in the final models panel is the weighted mean model, this is the model used in the waveform inversion. The colorbar (common to the top and bottom right panels) indicates the misfit between the observed and synthetic dispersion curves. Initial models in the bottom left panel are color-coded according the misfit in the corresponding final model. The best final models that reproduced the data were the ones that had the Moho depth (42 km in SPB case) fixed and one model with constant velocity (light blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ranges in which solutions with a good waveform fit can be obtained. Testing like that has also another aim: investigation of the solution stability.

The frequency range test in this paper extends between 0.01 and 0.15 Hz, using at least 0.03 Hz bandwidth. This minimum width was obtained by trial error after preliminary tests. We start the inversion using the frequency range of 0.01–0.04 Hz, followed by 0.01–0.05 Hz up to 0.01–0.15 Hz. Then we continue with 0.02–0.05 Hz until the last range test of 0.12–0.15 Hz. In total, we perform the inversion using 78 different frequency ranges (Fig. S2).

3. Studied events and 1-D path-specific velocity models

We choose three events to demonstrate the usefulness of specific path-dependent 1-D velocity models in the moment tensor inversion at relatively large regional epicentral distances: two rare Brazilian events with magnitude m_b larger than 4.5, and one Mw 5.3 earthquake that occurred in Greece.

A) Offshore event (São Vicente earthquake)

The 5.2 m_b earthquake of April 23, 2008 was located in the continental margin of Southeast Brazil. Assumpção et al. (2011), in their Fig. 4, show four hypocenter solutions – USGS (United States Geological Survey), ISC (International Seismological Center) and two regional locations using Brazilian stations with two different velocity models. These locations differ by as much as 20 km, mainly because the event occurred offshore and the closest stations were about 300–500 km away from the epicenter, all to the west and north of the event.

We choose the location and origin time determined by the Brazilian regional stations (denoted A71 by Assumpção et al., 2011), which is based on closer stations and better azimuthal distribution than USGS or ISC. The earthquake depth was fixed at 10 km by ISC and USGS hypocenters. Assumpção et al. (2011) obtained a depth of 17 km using pP-P time difference from North American, African and Antarctic stations situated between distances of 40° and 100°, with a P-wave velocity profile characteristic of the epicentral area (Fig. 7a from Assumpção et al., 2011).

The focal mechanism, obtained by Assumpção et al. (2011) through 48 P-wave first-motion polarities data at regional and

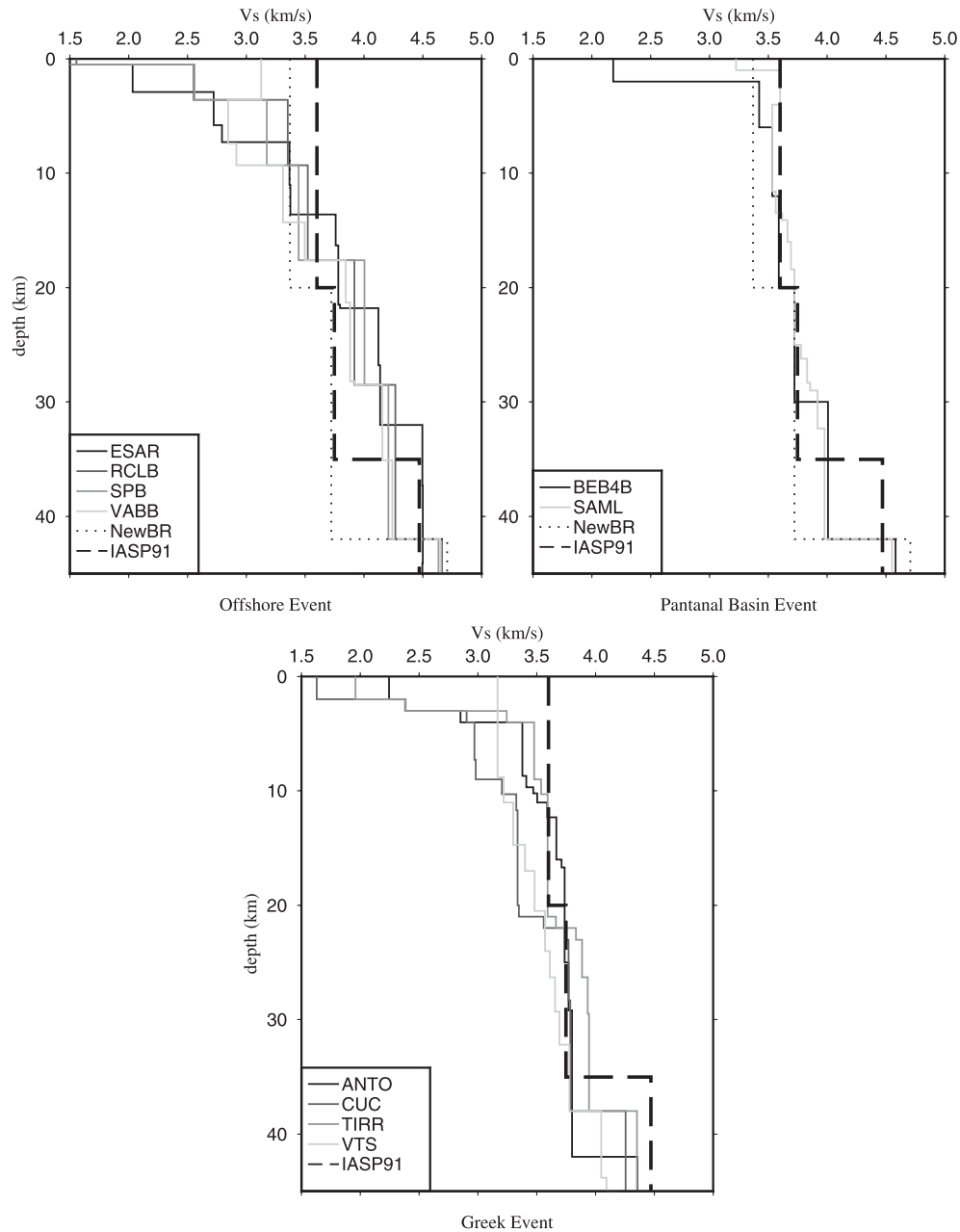


Fig. 2. S-wave velocity profiles derived from the Rayleigh and Love dispersion, used to calculate the Green's functions for the Offshore event (**top-left**), Pantanal Basin event (**top-right**) and Greek event (**bottom**).

teleseismic stations, was strike/dip/rake $341^{\circ}/89^{\circ}/93^{\circ}$. The focal mechanism was also constrained by SH-wave first-motion polarity at the six closest stations, as well as by pP/P amplitude ratios at teleseismic distances. This event showed an uncommon focal mechanism with one nearly vertical and the other nearly horizontal nodal plane. This was interpreted as due to flexural stresses in the bottom part of the crustal brittle layer in the transition between compressional and extensional stress domains.

We determine the path-specific velocity models from dispersion analyses at four stations (ESAR, SPB, VABB and RCLB). The obtained velocity models for the stations, as well as the IASP91 (Kennett and Engdahl, 1991) and NewBR (Assumpção et al., 2010) models are shown in Fig. 2. We use $V_p/V_s = 1.71$ based on the Wadati diagram of the event measured by Assumpção et al. (2011) to derive the V_p profiles. The waveforms were inverted using these four closest

Brazilian broadband stations 300–450 km away (map of Figs. 3 and 4).

B) Pantanal Basin event (Coxim earthquake)

On June 15th, 2009, a mb 4.8 event occurred in the Pantanal Wetland in Central-West Brazil. This event was studied by Dias et al. (2016). It is the second largest earthquake in the region, only surpassed by a mb 5.4 in 1964. We use the preferred epicenter, the one published by IDC (International Data Center, Vienna), as it is closest to the highest observed intensity, MM V (Modified Mercalli), in the epicentral area (Fig. 3 of Dias et al., 2016).

A reverse faulting mechanism, with transcurrent component, was obtained through 56 P-wave first-motion polarities data from regional and teleseismic stations, strike/dip/rake $300^{\circ}/55^{\circ}/45^{\circ}$.

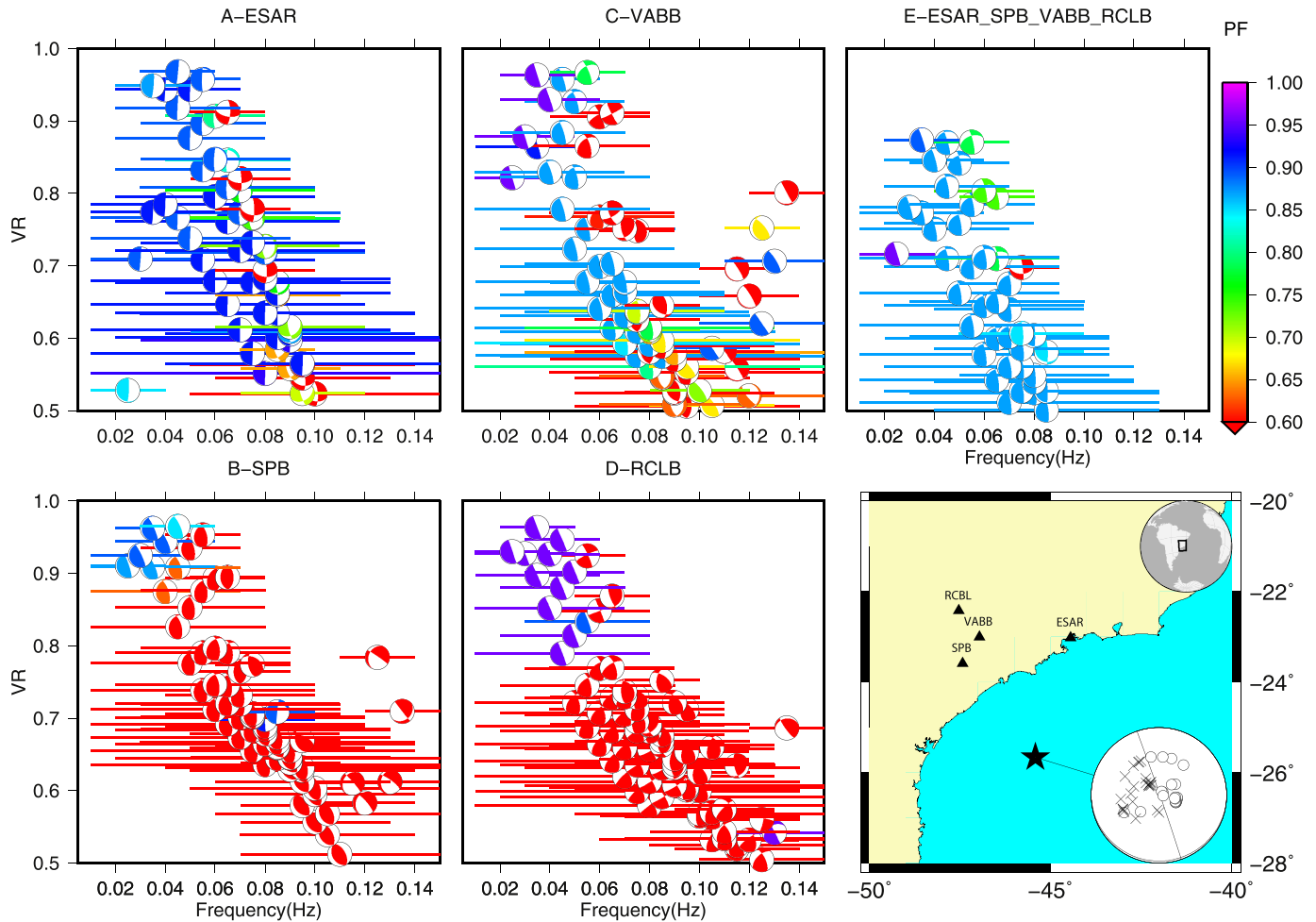


Fig. 3. Frequency range test for the Offshore event using the velocity models derived from the dispersion analysis. The horizontal bars (with the double-couple beachballs in the middle) denote the used frequency ranges. The variance reduction (VR) of the seismograms is indicated in the vertical axis. **Panels A, B, C and D** show the frequency range test for the each station used in the waveform inversion. **Panel E** shows the test using the four-station inversion. The beachballs are color-coded according to the fitted first motion polarities (see the colorbar denoted PF). **The bottom-right panel** shows the map with the epicenter location (star), the broadband stations (triangles), the P-wave polarities (crosses - compression, circles - dilatation) and the inset map. The focal mechanism from Assumpção et al. (2011) is plotted with the polarities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This focal mechanism was confirmed by teleseismic P, pP and sP waveform modeling of North American and South Pole stations, which gave a depth of 6 km (Dias et al., 2016).

In this work, we perform full waveform inversion using the closest broadband regional station (BEB4B), located 800 km away, and SAML station at 1300 km (Figs. 5 and 6) with the dispersion-based velocity models. Based on the NewBr velocity model from Assumpção et al. (2010), we choose $V_p/V_s = 1.78$ to derive P-wave velocity. The velocity models for both stations as well as NewBr and IASP91 models are again in Fig. 2.

C) Greek event (Efpalio earthquake)

For further testing the methodology, an independently and thoroughly studied event has been chosen. It is a shallow normal-faulting Mw 5.3 event, occurred on January 18, 2010 at 15:56 UTC in the western Corinth Gulf (Greece), the so-called Efpalio earthquake (Sokos et al., 2012). The centroid moment tensor (CMT) parameters of the earthquake are as follows: depth of 4.5 km and strike/dip/rake $102^\circ/55^\circ/-83^\circ$. The CMT solution was obtained with 8 near-regional stations (distance of 10–100 km) in the frequency range 0.05–0.10 Hz, with a very good waveform fit (VR 0.80) and large double-couple percentage (DC~90%). Note that in

this case the minimum shear wavelength (MSW) is ~30 km, hence the most distant station is as close as ~3 MSW from the source.

The focal mechanism is very stable within a few kilometers of the optimum source position, both in the horizontal and vertical direction. Luckily, a permanent GPS station was available near the epicenter, which made it possible to verify the CMT parameters by modeling the observed static displacement. Moreover, the CMT position agreed well with the location of the major slip patch obtained by the finite-fault modeling in the same paper. That is why the focal mechanism of this event is well constrained and can be used as a reference solution.

Although, for this event, closer stations were available, we perform the waveform inversion for four stations situated 400–1000 km away from the event, thus allowing comparison of the results with the Brazilian earthquakes. The V_s velocity models derived from the surface-wave dispersion are shown in Fig. 2. We choose the standard value $V_p/V_s = 1.73$ to obtain the V_p model.

4. Results of waveform inversion

The waveform inversion is made with the path-specific 1D velocity models as well with the regional NewBr and global IASP91 models, discussed in the previous section (Fig. 2).

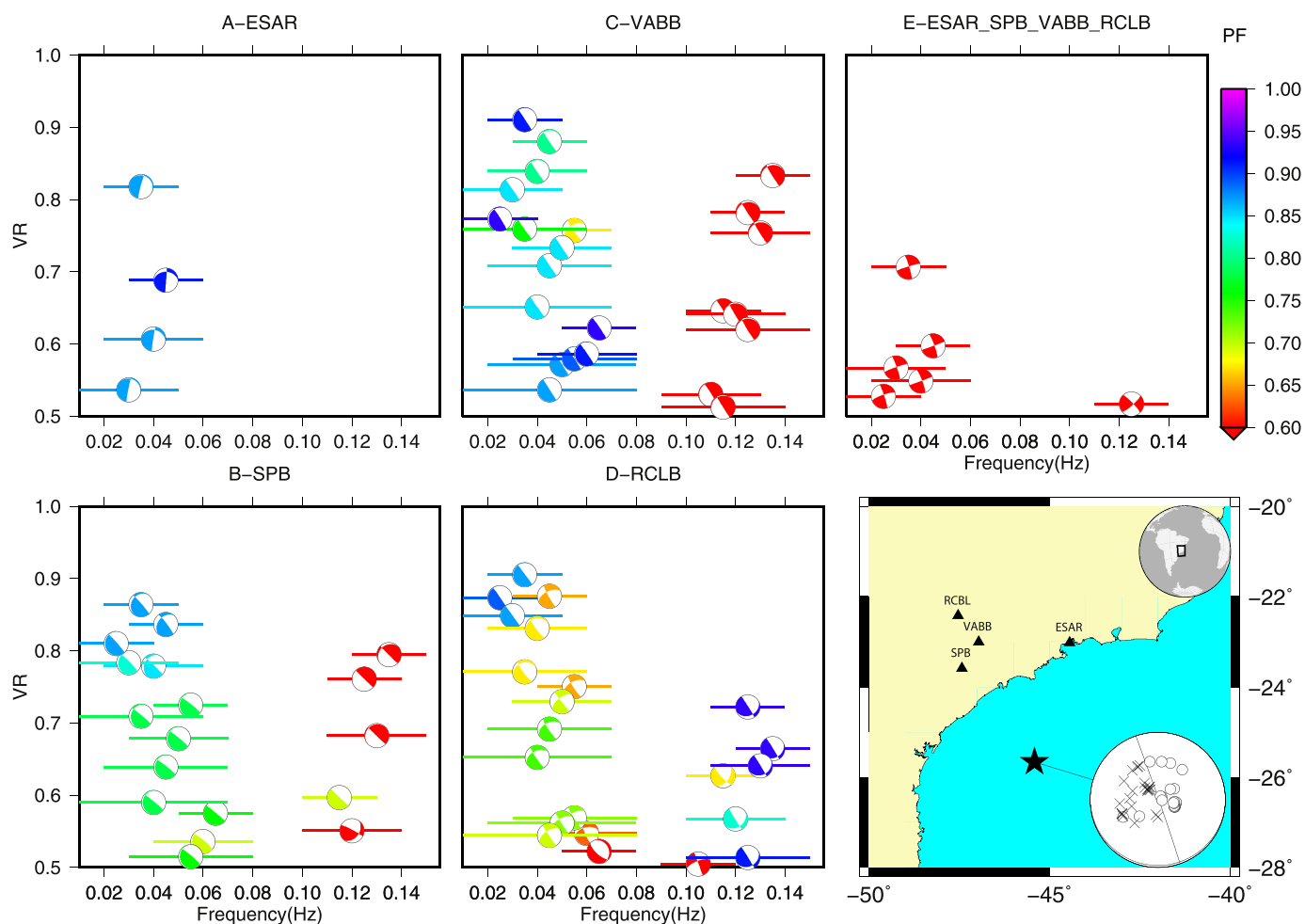


Fig. 4. Frequency range test for the Offshore event using the IASP91 velocity model for all source-station paths. The rest of caption is the same as in Fig. 3.

A) Offshore event

Fig. 3 shows the frequency range test for the Offshore event using the path-specific velocity models. We compare the individual single-station waveform inversions and the four-station inversion. In all these cases we plot the resulting mechanisms with VR larger than 0.5. The varying frequency ranges cover the interval of 0.01–0.15 Hz. The solutions are color-coded according to their polarity fit (PF), e.g., PF = 0.90 means that polarities at 90% of the stations are satisfied. In this case, we are using 48 polarities. We find that, systematically, the solutions with higher VR are concentrated at lower frequencies. It is because low frequencies are modeled more easily and also they are not much dependent on the thin layer velocities. At each single source-station path we were able to recover a solution that can explain the waveform at high VR and, simultaneously, it fits most of the P-wave first motion polarities (see the beachballs with PF > 0.90 in the top-left parts of panels A–D of Fig. 3). These solutions are very close to the polarity solution of Assumpção et al. (2011), which has a PF of 0.96.

In panels B and D of Fig. 3, there are many solutions, showing poor fit to the polarities. Although some of these solutions have high VR, a slight rotation with respect to the mechanism from Assumpção et al. (2011) causes their disagreement with some polarities close to the central part of the focal sphere. Simply speaking, the focal mechanism of the Offshore event is strongly constrained by the polarities themselves; the polarities are numerous and have a good azimuthal coverage. The fact that many solutions in panels

A–D of Fig. 3 found by waveform inversion agree also with polarities is a strong indication that the derived velocity models are appropriate.

In panel E of Fig. 3, we demonstrate the result of inverting simultaneously all four stations, considering each one with its specific 1D path model. The solutions featuring high VR again fit most polarities; naturally the best VR is lower than in the single-station inversions, but still the waveform fit is very good for four stations (VR > 0.90). A notable feature is the presence of three strike-slip solutions featuring also a relatively high VR > 0.80. They can be discarded due to their significant polarity misfit (PF < 0.75). Nevertheless, this result is important because it shows that an incorrect solution with high VR can be obtained in certain frequency ranges. If only few polarities were available, it would be difficult to recognize that the strike-slip solutions are incorrect. The only indication of their inappropriateness would be perhaps that they are less abundant with respect to the reverse mechanisms.

Note that the satisfactory solutions were obtained up to 0.13 Hz. For Vs ~3.0 km/s, the minimum shear wavelength (MSW) is about 23 km. Since the furthest station, RCBL, is situated at the epicentral distance of 430 km, the path-specific velocity models allowed us to model waveforms successfully up to 19 wavelengths. This is a considerable improvement against use of common models, typically allowing modeling up to ~10 MSW only.

Table 1 summarizes the inversion results for the frequency range test of the Offshore Event under condition of variance reduction >0.50 and polarity fit >0.60. From the 78 tested

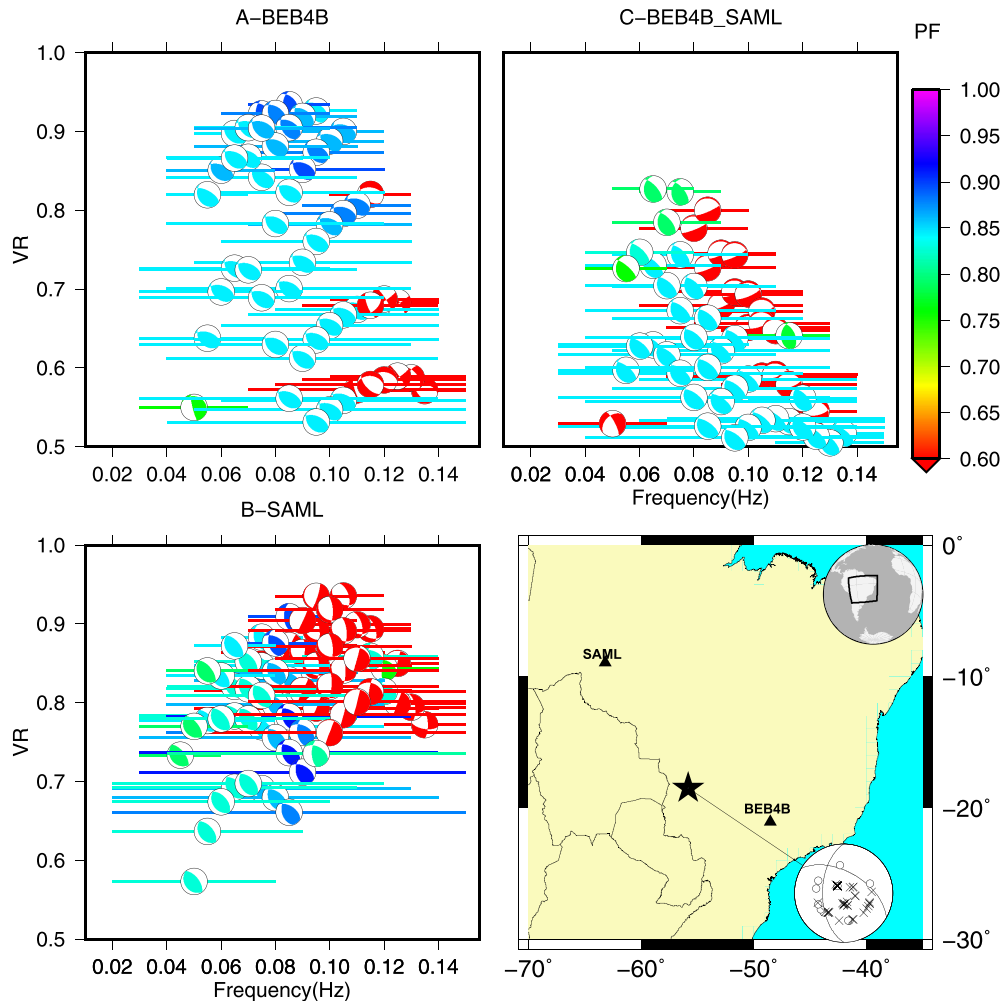


Fig. 5. Frequency range test for the Pantanal Basin event using the velocity models derived from the dispersion analysis. The rest of caption is the same as in Fig. 3. The focal mechanism and polarities in the bottom-right panel are from Dias et al. (2016).

frequency ranges, 41 were able to fit these criteria. We present the intervals of the inverted parameters and their respective medians. The low number of solutions for SPB and RCLB stations is due to the slight rotation of the mechanism, already explained above.

For all stations, the centroid time shift (CT) with respect to the origin time is small, less than 1 s in absolute values. The centroid depth for all stations has a median value of 27 km, but, as we explained later, the depth resolution is not good. The median of the double-couple percentage is large (87%).

A much worse result is obtained by inverting the Offshore event with the global IASP91 velocity model (Fig. 4). For each panel, the number of solutions and their VR significantly decrease with respect to Fig. 3, and there is no solution of $VR > 0.50$ in any broad frequency range. This means that the IASP91 model is definitely less appropriate than the path-specific models. Nevertheless, in panels A–D of Fig. 4 we can find a few solutions with a relatively high VR and PF.

An interesting effect can be seen in Fig. 4, panel C. It shows some ‘flipped’ mechanisms for frequencies larger than 0.10 Hz. This ambiguity exists in waveform inversion when a narrow frequency band is used. In some cases, the rake angle could be altered in 180° to improve the data fit. According to Zahradník et al. (2005, 2008) a narrow frequency band in the inversion makes the seismograms close to sinusoidal, and so a time shift of half-period would also match the seismogram by changing the rake by 180° .

Despite each single-station inversion recovered a few good solutions, the four-station inversion in model IASP91 (panel E in Fig. 4) contains only strike-slip mechanisms, with a poor polarity agreement. The fact that single-station inversions were capable to find a few acceptable mechanisms, but joint inversion of four stations was not, can be explained easily: the single-station inversions may differ from each other in the centroid depth and time, as well as in Mw. The joint inversion has less freedom, as it seeks a common depth and Mw, preventing the best fit to be found when all stations are used together.

The last velocity model used to perform the inversion is the regional velocity model for Brazil, NewBR. The frequency range test is shown in supplementary material (Fig. S3). The result is similar to the IASP91 model: few acceptable mechanisms (high VR and high PF in panel A) exist in narrow frequency ranges, ‘flipped solutions’ can be found in some single-station inversions, incorrect strike-slip solutions are present in the four-station inversion (panel E), and just one acceptable solution with good polarity agreement in the four-station inversion.

An example of the waveform fit for the Offshore event is shown in Fig. S4 using the frequency range of 0.02–0.06 Hz and the velocity models derived from the dispersion analysis. The solution shows a high VR of 0.85, a Mw 4.7, 94% of DC component, centroid time shift of -0.56 s and PF of 0.87. Although, formally, the best-fitting centroid depth is 14 km, close to 17 km published by

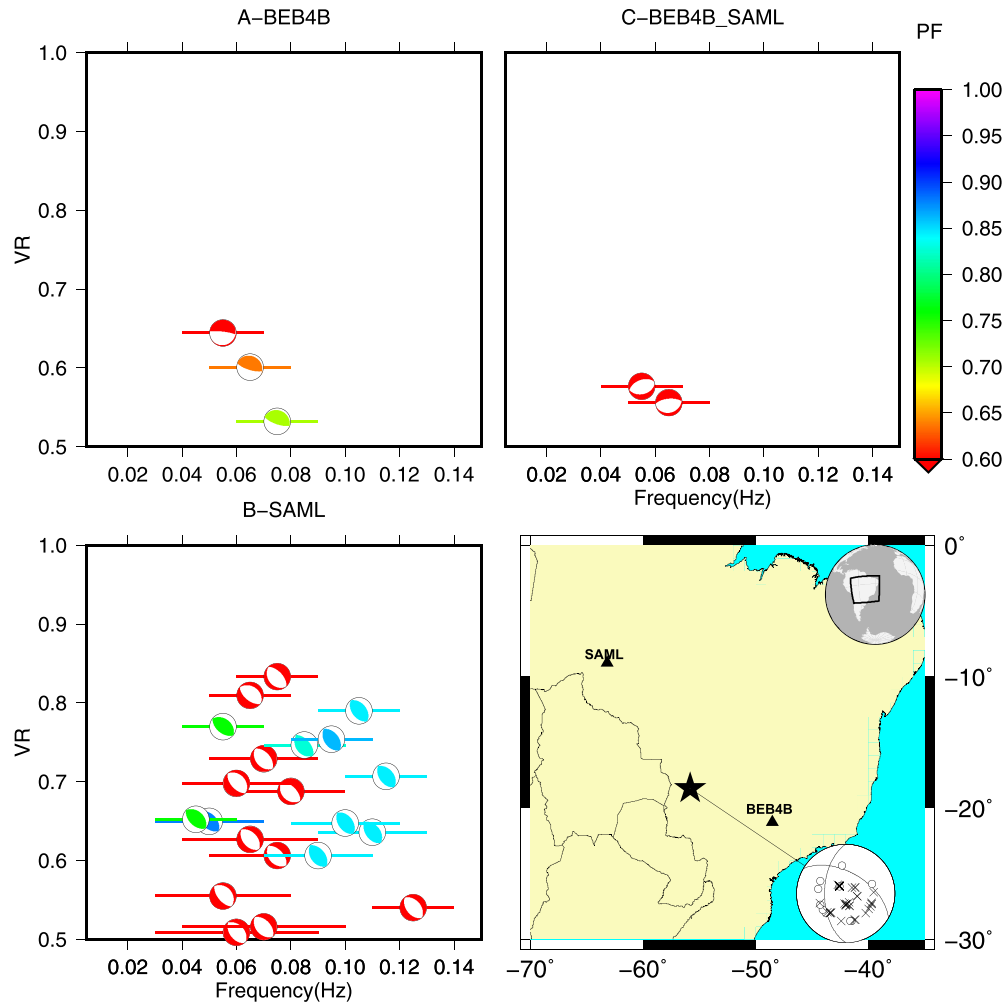


Fig. 6. Frequency range test for the Pantanal Basin event using the IASP91 velocity model for all source-station paths. The rest of caption is the same as in Fig. 3.

Assumpção et al. (2011), there is no resolution for this parameter; the depths between 10 and 29 km provide $VR > 0.50$. The Kagan angle (Kagan, 1991) between our preferred solution and the one from previous study is 18° , i.e., similar mechanisms.

B) Pantanal Basin event

The frequency range test for the Pantanal Basin event using the path-specific velocity models from the dispersion analysis is shown in Fig. 5. For this 4.8 mb earthquake, we were just able to find two stations with a high signal-to-noise ratio and a clear Rayleigh and Love group velocity dispersion.

In this case, we are using 56 polarities and, for BEB4B station, shown in panel A of Fig. 5, almost all solutions are reverse faults with high PF (>0.85). Many of them have a very good waveform fit ($VR > 0.90$). In panel B, SAML station, the solutions with highest VR do not agree with polarities (low PF); this again emphasizes the importance of the polarity constraint; the preference of the solution based just on the highest VR, is dangerous, mainly for a single station.

The joint inversion for both stations is similar to the Offshore event. We obtain two types of the mechanism: the reverse and normal fault, while the reverse one has a good fit of the polarities and they are also more abundant.

Using the surface waves velocity models, we are able to invert frequencies up to 0.15 Hz with acceptable VR. The SAML station (a

100 m borehole station) is located approximately at 1300 km from the earthquake, i.e., for the Pantanal Basin event we can model waveform up to 65 MSW. Note the absence of the solutions for the lowest frequencies 0.01–0.03 Hz. For both stations, the seismograms were too noisy in that band to be successfully inverted.

The summary of the centroid parameters is shown in Table 2. The median value of the difference between centroid time and origin time is lower than 1.5 s for all cases, which is perfectly acceptable since we are dealing with stations further than 800 km. Note that magnitude for the single-station SAML inversion is higher and the median depth is shallower than for BEB4B. It is possible that due to these differences in the single-station inversions we obtain a very low double-couple percentage ($DC = 26\%$) in the joint two-station inversion.

On the other hand, in the waveform inversion made with the IASP91 model, just a few and low-PF solutions were found using just the BEB4B station (Fig. 6). The SAML station inversion is a bit more successful; it shows mechanisms with a good PF or 'flipped' solutions for the relatively broad ranges (0.04–0.10 Hz). Joint inversion of both stations is not good at all, it provides just two normal solutions with low PF. Equally problematic is the inversion with the NewBR regional model, shown in Fig. S5. The inversion for BEB4B has a few good PF mechanisms and some flipped solutions and there are just three solutions for SAML station. For the joint two-station inversion, the panel is empty because the best mechanism had VR of 0.34 and PF of 0.24.

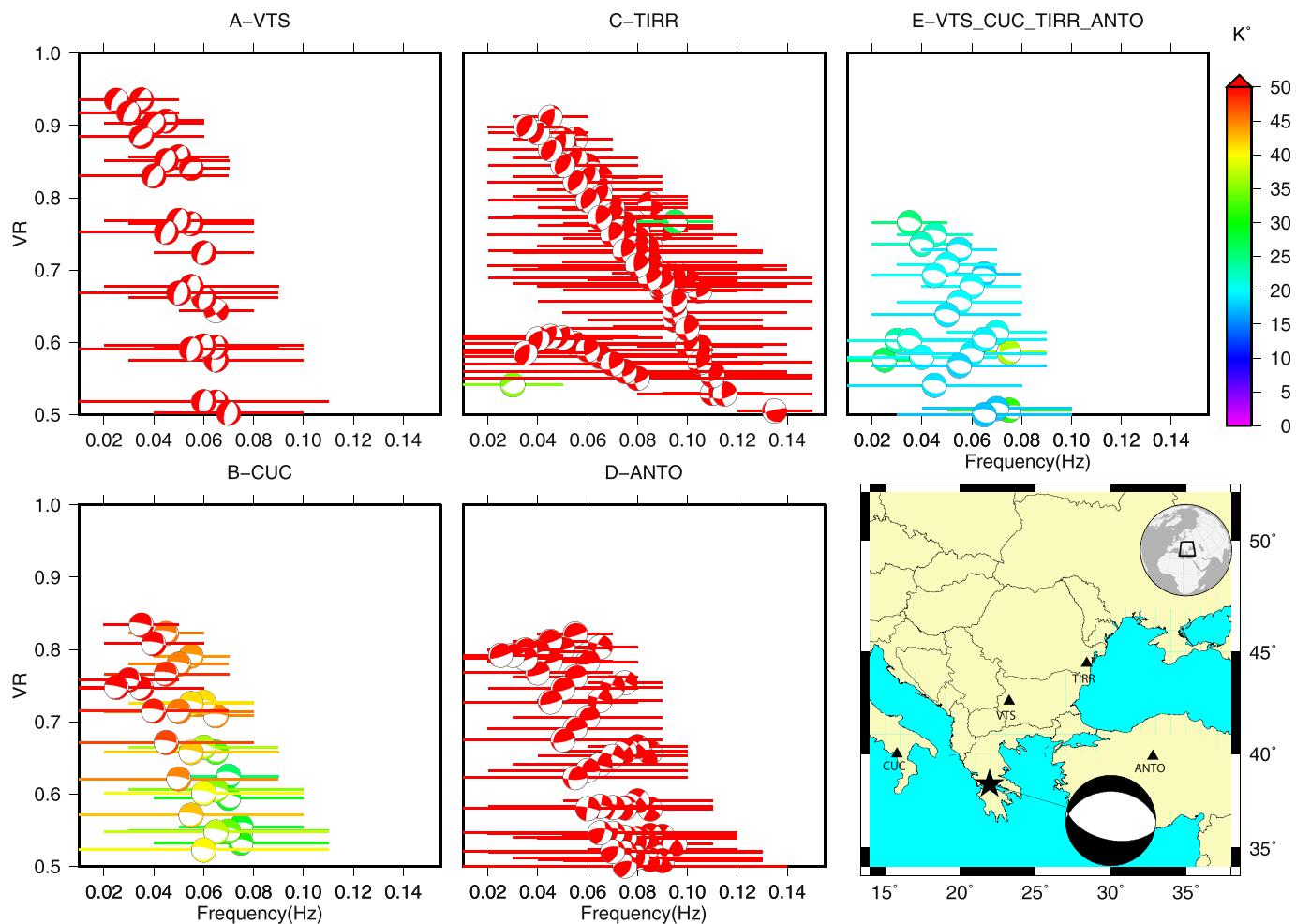


Fig. 7. Waveform inversion of focal-mechanism for the Greek event, using the velocity models derived from the dispersion analysis. The rest of caption is the same as in Fig. 3. The beachballs are color-coded according to the Kagan angle difference with respect to the reference solution from Sokos et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary of the moment tensor inversion parameters for Offshore event, considering variance reduction >0.5 and polarity fit >0.6. The range of values is shown, followed by their median in parenthesis. The symbols denote N (number of the solutions; <= 78), CT (centroid time shift with respect to origin time), Mw (moment magnitude), DC% (double-couple percentage), PF (polarity fit), VR (variance reduction).

Station	N	CT (s)	Mw	Depth (km)	DC (%)	PF	VR
ESAR	51	−1.9/2.7 (0.2)	4.8/4.9 (4.8)	24/30 (30)	26/80 (62)	0.65/0.93 (0.89)	0.52/0.97 (0.72)
SPB	10	−1.0/0.8 (−0.5)	4.7/4.8 (4.8)	10/26 (20)	65/96 (76)	0.63/0.91 (0.88)	0.70/0.96 (0.90)
VABB	47	−5.0/3.0 (−0.7)	4.5/4.9 (4.7)	05/30 (27)	11/96 (61)	0.60/0.96 (0.87)	0.50/0.97 (0.64)
RCLB	13	−1.9/4.7 (−1.0)	4.8/4.9 (4.9)	07/30 (28)	44/96 (87)	0.89/0.96 (0.95)	0.54/0.96 (0.89)
All	41	−1.3/1.4 (0.2)	4.7/4.8 (4.7)	10/29 (27)	56/97 (87)	0.73/0.96 (0.87)	0.50/0.87 (0.65)

Table 2
Summary of moment tensor inversion parameters for Pantanal Basin event, considering variance reduction > 0.5 and polarity fit > 0.6. The rest of the caption is the same as in Table 1.

Station	N	CT (s)	Mw	Depth (km)	DC (%)	PF	VR
BEB4B	43	−1.3/1.3 (0.4)	4.3/4.6 (4.5)	03/10 (07)	55/99 (89)	0.76/0.90 (0.84)	0.53/0.93 (0.80)
SAML	38	−1.1/2.6 (1.3)	4.7/5.2 (5.0)	02/11 (03)	41/99 (75)	0.75/0.91 (0.83)	0.57/0.90 (0.78)
All	36	1.1/2.3 (1.4)	4.4/4.6 (4.6)	06/11 (08)	14/40 (26)	0.75/0.94 (0.84)	0.50/0.82 (0.60)

The waveform fit for the two-station inversion with path-specific models is shown in Fig. S6. The solution was obtained using the range of 0.05–0.08, a Mw 4.5, centroid time shift of 1.8 s and PF of 0.81. Although the double-couple component is low (19%), we

were able to fit the data with high variance reduction 0.84, and depth 9 km is in good agreement with 6 km obtained from teleseismic P-wave waveform modeling from Dias et al. (2016), which has a mechanism with PF of 0.93. The Kagan angle between our

preferred solution and the one from previous study is 25° , therefore indicating similar mechanisms.

C) Greek event

In the present study, regional station records situated 400–1000 km away from the Greek event were retrieved from IRIS (Incorporated Research Institutions for Seismology) database center (www.ds.iris.edu/wilber3/find_event). They were manually checked and those with good signal-to-noise ratio were chosen. As for Brazilian earthquakes, we use records with at least 10 s of clear and unambiguous dispersion curves in vertical and transversal components. The path-specific velocity models resulting from the surface-wave dispersion analysis, and also the reference model IASP91, are shown in Fig. 2.

Fig. 7 provides the frequency range test for the Greek event using the path-specific velocity models for four stations, VTS, CUC, TIRR and ANTO. Differently from the previous plots, the focal mechanisms in Figs. 7 and 8 are color-coded according to Kagan angle (K-angle), measuring the minimum angular rotation with respect to the reference solution of Sokos et al. (2012). Focal mechanisms can be considered as similar for K-angles less than $20\text{--}30^\circ$ and highly dissimilar for $>40^\circ$ (Zahradník and Custódio, 2012).

We see that for the individual stations VTS, TIRR and ANTO, (panels A, C and D of Fig. 7), the retrieved mechanisms have K-angle $> 50^\circ$. In other words, although featuring large VR and great stability they do not recover correctly the reference solution. There are basically two reasons for such a behavior, either the velocity model is still not yet appropriate enough, or the single station inversion is too ill-posed (more than one solution), or both. At station CUC (panel B) the situation is similar, although at lower VR values we obtain solutions closer to the reference.

Contrarily to the single-station inversions, the joint waveform inversion of the four stations, each one with its path-specific model (panel E), gives focal mechanisms close to the reference solution of Sokos et al. (2012). Note that in this case the solutions of $VR > 0.50$ exist only for frequencies below 0.10 Hz. Nevertheless, considering the furthest station (ANTO) located at 950 km from the epicenter, we find that the path-specific velocity models allowed us to model waveforms successfully up to as much as ~ 31 MSW.

Table 3 shows the summary of parameters for the waveform inversion. The median of the centroid versus origin time shift is lower than 2.2 s for all stations, which is still acceptable because we are dealing with stations more distant than 400 km. Depths are variable because these single station inversions do not have enough resolution; e.g., for VTS station with $VR > 0.50$ is obtained depths between 2 and 22 km. For all stations the resolution is better,

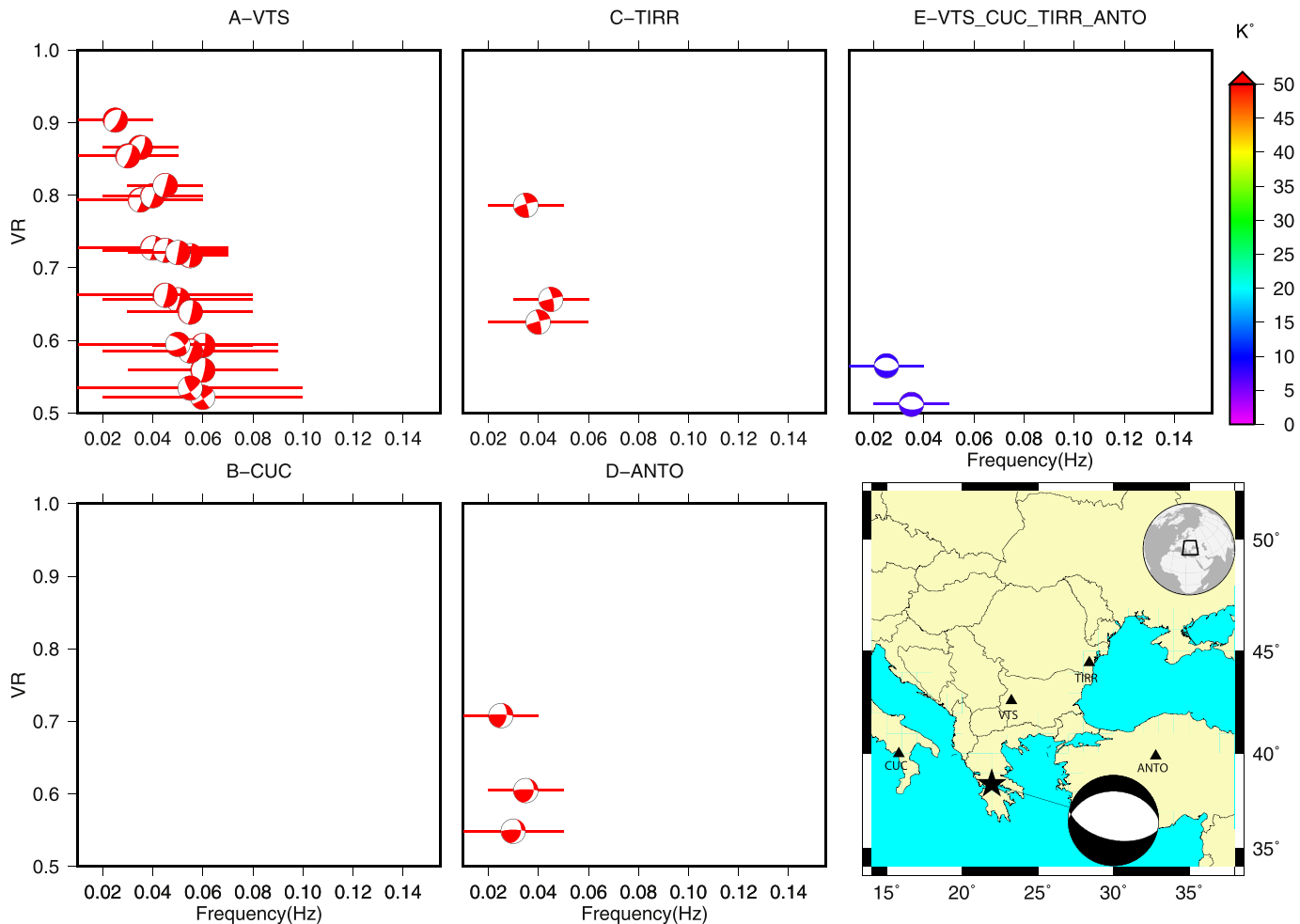


Fig. 8. Waveform inversion of focal-mechanism for the Greek event, using the IASP91 velocity model. **Panel B** is empty because there are no solutions within the considered range of frequencies and VR values. The rest of caption is the same as in Fig. 3. The beachballs are color-coded according to the Kagan angle difference with respect to the reference solution from Sokos et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Summary of moment tensor inversion parameters for Greek event, considering variance reduction > 0.5. The rest of the caption is the same as in Table 1.

Station	N	CT (s)	Mw	Depth (km)	DC (%)	VR
VTs	25	−2.1/4.9 (−1.3)	5.4/5.7 (5.5)	02/22 (04)	25/93 (55)	0.50/0.93 (0.75)
CUC	30	−1.9/−0.4 (−1.1)	5.1/5.3 (5.2)	22/22 (22)	16/98 (76)	0.52/0.83 (0.67)
TIRR	70	−2.6/1.7 (−2.2)	5.1/5.7 (5.5)	05/22 (19)	03/99 (18)	0.50/0.91 (0.70)
ANTO	48	−5.0/1.3 (−1.9)	5.2/5.8 (5.5)	12/22 (19)	06/76 (30)	0.50/0.82 (0.65)
All	23	−3.1/−1.0 (−1.8)	5.1/5.4 (5.2)	04/07 (05)	67/92 (75)	0.50/0.76 (0.60)

providing VR > 0.50 in the range of 4–7 km.

Using IASP91 velocity model (Fig. 8), we have approximately the same wrong behavior as for the Brazilian earthquakes: both the number of solutions and their VR values drop down; in the limiting case of station CUC (panel B) there is no mechanism with VR > 0.50. The reference solution was correctly retrieved in the joint inversion, but just in two narrow low-frequency ranges.

An example of waveform match for a good solution obtained with the path-specific velocity models is presented in Fig. S7 using the frequency range of 0.02–0.06 Hz. The solution is characterized by VR of 0.72, Mw 5.3, 75% of DC component and centroid depth of 5 km, i.e. with CMT parameters close to those of Sokos et al. (2012). The Kagan angle between the solutions is 22°.

5. Discussion of focal mechanisms

Comparing the waveform inversion results of the two Brazilian events using IASP91 and NewBr models to those obtained using the path-specific velocity models (derived from the dispersion analysis), we conclude that the latter significantly increase the quality of the moment tensor calculation. The number of solutions with a high polarity fit and high VR values increased with the path-specific models. Another notable fact is the bandwidth of the inversion. For IASP91 and NewBR models the VR > 0.5 mechanisms were just obtained for narrow frequency range of 0.03 and 0.04 Hz, while the path-specific models performed well in the considerably broader range of 0.01–0.14 Hz.

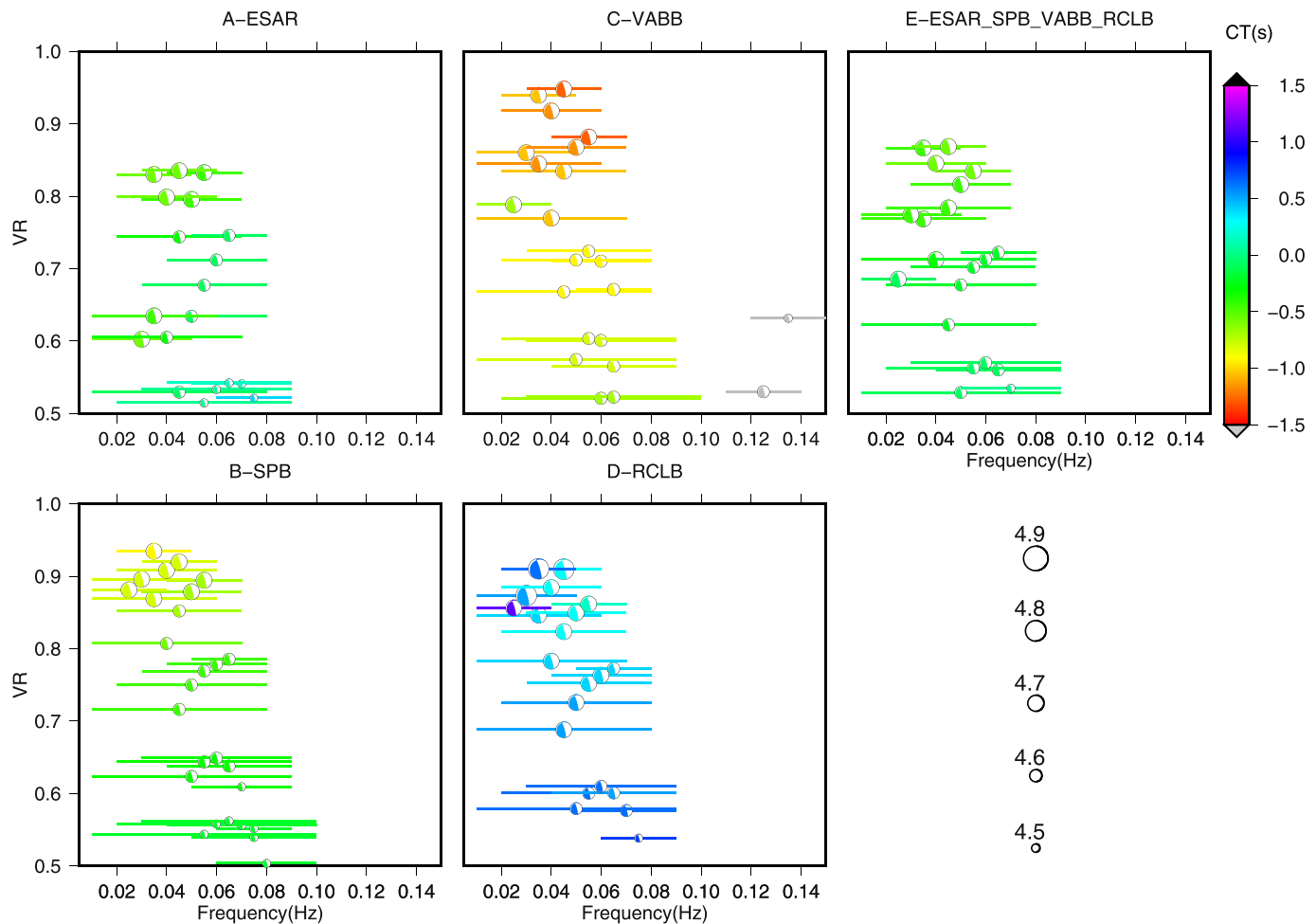


Fig. 9. Posterior check of the reliability of the velocity models for Offshore event. The horizontal bars (with the double-couple beachballs in the middle) denote the used frequency ranges. The variance reduction (VR) of the seismograms is indicated in the vertical axis. **Panels A, B, C and D** show the frequency range test for the each station used in the waveform inversion. **Panel E** shows the test using the four-station inversion. The beachballs are color-coded according to centroid time shift in seconds with respect to origin time (see the colorbar denoted CT). The size of the beachballs is Mw magnitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Does the frequency range test help in recognizing correct focal mechanisms? Waveform inversion of the Brazilian events, made with path-specific models, revealed that some of the high-VR solutions in certain frequency ranges agree with polarities, but some solutions do not agree, e.g., the strike-slip mechanisms in Panel E of Fig. 3 and the normal mechanisms in Panel C of Fig. 5. It means that simple classification based on high VR is not sufficient, and a check of the mechanism against (numerous and well distributed) polarities is very useful.

The frequency with which a particular focal-mechanism solution appears in the frequency range test is also a useful parameter. For example, in the case of the Offshore event, we could discard the wrong strike-slip solution because it appeared just once, in contrast to the stable and numerous mechanisms of the low-angle reverse-fault type. The situation is less favorable for the Pantanal Basin event (Panel C of Fig. 5), where the normal-faulting (wrong) solutions represent as much as 1/3 of the mechanisms. The double-couple percentage, in this case, also does not help to discard the normal mechanisms; indeed, their DC% is high (median of 60%), while double-couple percentage of the (correct) reverse mechanisms is low (median of 26%, see Table 2). For this event, the frequency range test just indicated that the normal-fault solutions are less favorable, but the main reason to discard these solutions is the polarity fit, less than 0.6.

For the Greek event (Fig. 7), most of the mechanisms obtained from the single-station, path-specific inversions (except a few in

panel B) have their Kagan angle larger than 60° , i.e., those inversions did not correctly recover the reference solution. This is an important warning because, for the Brazilian events, the correct mechanisms appeared among the solutions shown by the frequency range test. The Greek event also shows that stability of the mechanism for different frequency bands is a necessary but not sufficient condition to obtain the correct solution, particularly in the single-station inversion. Note also that for the Greek event, we were able to model waveforms in the joint inversion up to 0.10 Hz, in contrast to 0.15 Hz for Brazilian earthquakes. A likely reason is lower accuracy at higher frequency of the path-specific 1-D velocity models derived for the Greek event, where the source-stations paths seem to be geologically more complex than in Brazil.

6. Posterior check of new velocity models

In regard of panels A–D in Figs. 3 and 5 for the Brazilian events we have stressed that many solutions provided by the waveform inversion also agreed with polarities, thus indicating that the path-specific velocity models are appropriate. However, we have encountered also single-station inversions, mainly in Fig. 7 for Greek event, which do not provide the correct mechanism. Is that because some path-specific velocity models derived in this paper are inappropriate? It is easy to show the opposite, i.e., that most of the velocity models are reasonable.

Such a posterior validation of the velocity model is possible,

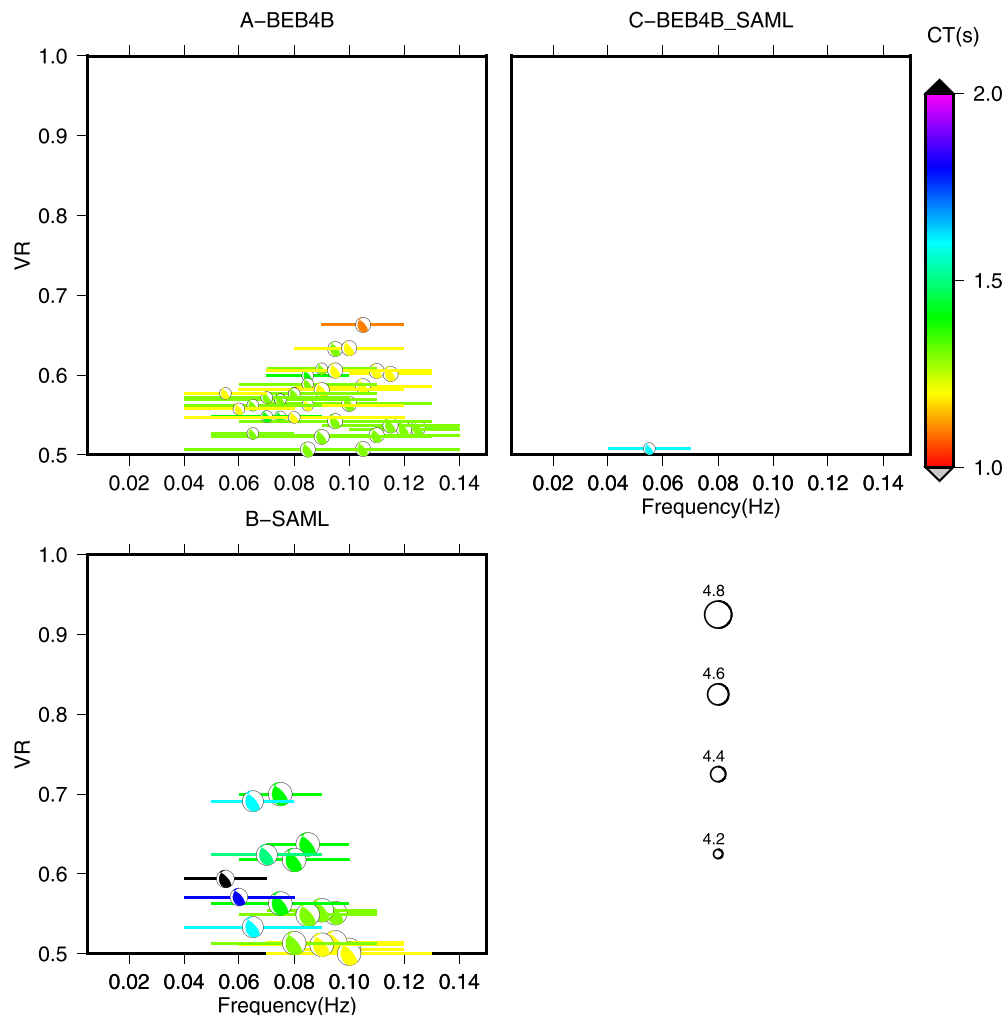


Fig. 10. Posterior check of the reliability of the velocity models for Pantanal Basin event. The rest of caption is the same as in Fig. 9.

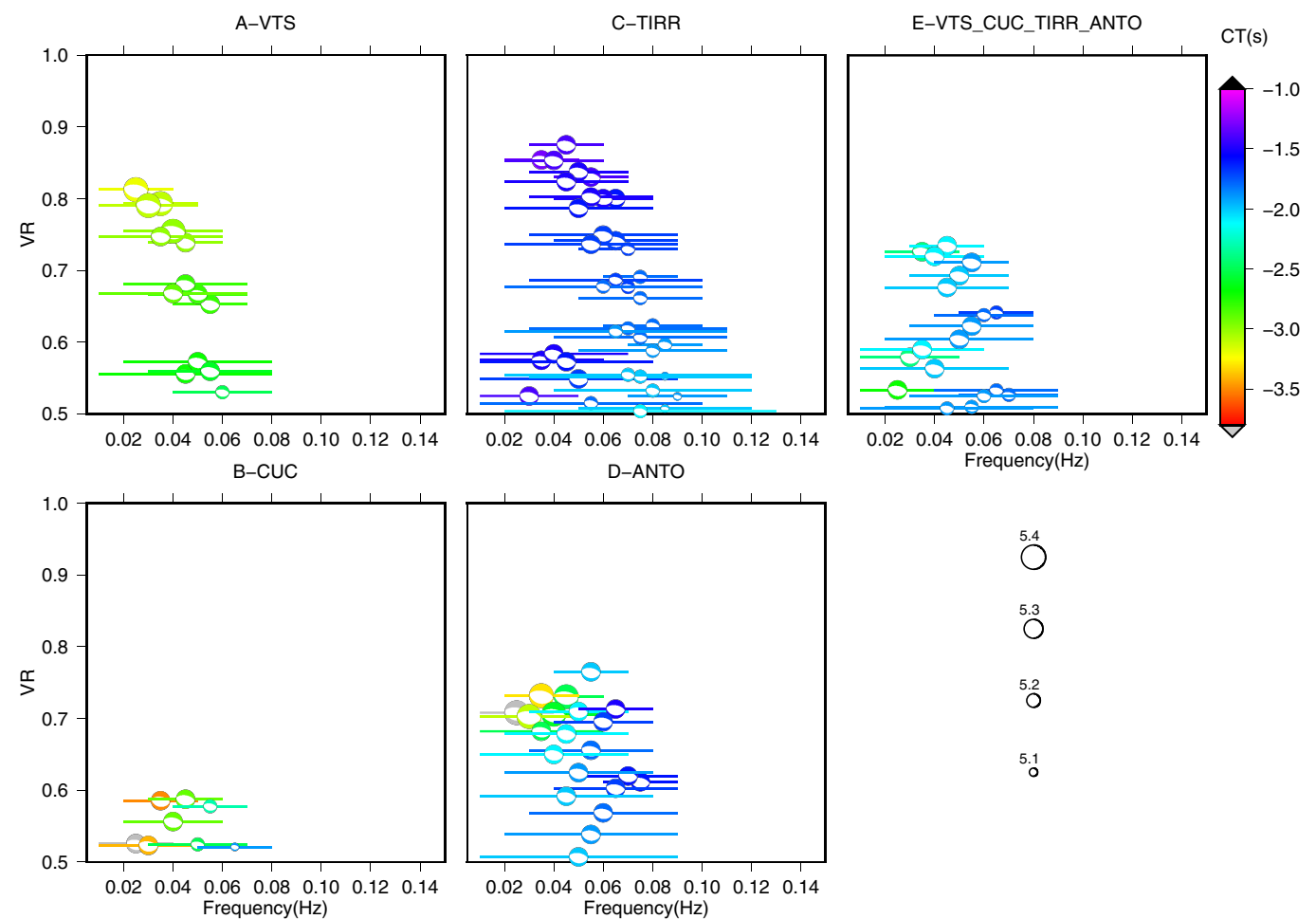


Fig. 11. Posterior check of the reliability of the velocity models for Greek event. The rest of caption is the same as in Fig. 9.

because (as shown above) the focal mechanisms of this paper were independently and previously tightly constrained. It means that we can keep the focal mechanisms fixed and ask how well the observed waveforms are matched. If the waveforms are fitted well, we confirm validity of the velocity model. The tests like that are presented in Figs. 9–11 for the Offshore, Pantanal Basin and Greek event, respectively.

The modeling makes use of a fixed source depth (= location depth) and focal mechanism (DC = 100%), while the centroid time varying between –5.0 and 5.0 s and Mo (hence Mw) are free. The fixed parameters are shown in Table 4 and they are the same as of Figures S4, S6, S7. Although these tests were performed for our preferred solution, similar results are obtained for the published focal solutions of the Offshore (Assumpção et al., 2011), Pantanal Basin (Dias et al., 2016) and Greek earthquakes (Sokos et al., 2012).

In Figs. 9–11 we inspect the quality of the waveform fit in terms of VR, while keeping fixed the focal mechanism and depth. The velocity model is considered adequate if obtaining enough solutions with high VR and reasonable CT and Mw. The beachballs are

color-coded by centroid time shift (CT) with respect to the origin time and the beachballs size scales with moment magnitude Mw. Each event has a different Mw and CT scale to better visualize the differences among the solutions. For the Offshore event, the CT is between –1.5 and 1.5 s. As expected, solutions with large VR correspond to higher magnitude, reaching 4.9 Mw for RCLB station and 4.5 Mw for solutions with VR ~0.5 for all panels. Naturally, the four-station modeling of Panel E in Fig. 9 shows fewer solutions than Panel E in Fig. 3, but still we have many mechanisms with small CT. For this event, we can conclude that the velocity models are successfully validated, because they are able to explain the waveforms and surface wave dispersion simultaneously.

For the Pantanal Basin earthquake (Fig. 10) the CT is also low, comprised between 2.0 and 1.0 s. The VR is lower than for the Offshore event but still acceptable; we were able to present solutions with VR > 0.5 for frequencies up to 0.13 Hz for the stations at 800 km and 1300 km from the earthquake. In Panel C, we have just one 100% DC solution, mainly because the joint inversion for both stations strongly required low double couple percentage while here

Table 4
Location and focal mechanism used to perform the posterior check of the reliability of the velocity models.

Event	Date	Origin time (UTC)	Lat (°)	Lon (°)	Depth (km)	Nodal plane (°)
Offshore	23-Apr-08	00:00:47.70	–45.273	–25.704	14	225/15/150
Pantanal Basin	15-Jun-09	22:15:45.16	–55.797	–18.513	9	182/30/130
Greek	18-Jan-10	15:56:09.80	21.941	38.422	6	98/34/–91

the 100% DC is constrained (see Table 2). We can affirm that velocity models for the Pantanal Basin are reasonable but less robust than for the Offshore event because the former included longer paths.

Fig. 11 shows the posterior check for the Greek event. The CT varied between -1.0 and -3.5 s for the individual stations, and between -2.0 and -2.5 s for the joint inversion. The magnitude is again higher at larger VR values. The result for CUC station (Panel B) shows fewer solutions and lower VR, indicating that the velocity model for that source-station path is probably less well resolved than the models for the paths between the source and stations VTS, TIRR and ANTO. It means that the absence of the correct solutions (high K-angle) in panels A, C and D of Fig. 7 was not simply linked with the quality of the velocity model, but rather linked to the ill-posed single-station inversion.

7. Conclusion

We introduced a methodology to calculate centroid moment tensors (CMT's) of moderate magnitude earthquakes ($M=4-5$) at large regional distances ($\sim 300-1300$ km). The methodology is based on *path-specific* velocity models derived from the Rayleigh- and Love-wave dispersion curves, followed by full waveform inversion, and accompanied by posterior check of P-wave first-motion polarities. An important innovation is the use of so-called *frequency range test*. The test basically consists in calculating CMT's for many different frequency ranges allowing us to check the stability and uncertainty of the solution.

The new methodology is validated on two Brazilian events (the 5.2 mb Offshore, and 4.8 mb Pantanal Basin) and further tested on an event from Greece (the 5.3 Mw Efpalio earthquake). The focal mechanisms of the Brazilian earthquakes had been previously calculated from polarities, while for the Greek event the solution was previously obtained from waveform inversion at closer regional stations and independently confirmed by GPS modeling. Therefore, the three events are excellent candidates for understanding effects of various velocity models upon the CMT inversion. In particular, we are able to compare the inversion performance with existing standard models (IASP91 and NewBR, each one used for all source-station paths), and with the path-specific models. The path-specific models, derived in the paper, differ from the standard models mainly in the topmost ~ 10 km, where they feature relatively low velocities, increasing with depth.

It has been unambiguously demonstrated that the path-specific velocity models significantly increase the reliability of the CMT's. These models recover correct focal mechanisms with much better waveform fit up to higher frequencies and more frequent occurrence in the frequency test diagrams than the standard models. While standard models typically allow waveform modeling up to epicentral distances of the order of just few (~ 10) minimum shear wavelengths (MSW), using the path-specific velocity models we successfully inverted waveforms up to > 20 MSW (i.e., 19, 65 and 31 for the Offshore, Pantanal Basin and Greek event, respectively), representing an important improvement.

The most reliable results for the Brazilian earthquakes were obtained in *joint* inversions of several (2–4) source-station paths, each one with its specific velocity model. These results, representing the main application of this paper, are shown in panel E of Fig. 3 and panel C of Fig. 5. The same figures (panels A–D for Fig. 3 and panels A–B for Fig. 5) demonstrate that *single-station* inversions with path-specific models are basically less reliable than the joint inversions. In particular, single-station inversions for the Greek event (panels A–D of Fig. 7) show that stability of the CMT solution is a necessary but not sufficient condition to constrain the solution. In general, CMT inversions from a few relatively distant stations, in particular the single-station inversions, may often be ill-posed (the

resolvability of the MT is limited). That is why even with reliable Green's functions from path-specific velocity models we may obtain a wrong focal mechanism. Non-double components are particularly vulnerable.

To solve the question why some single-station inversions do not provide correct focal mechanism, either because the problem is ill posed or rather the path-specific velocity models are still not adequate, we made a *posterior validation of the velocity models*. The check consisted in fixing the 100% double-couple focal mechanism from the multiple-station joint inversion (which agrees with polarities and/or with a previously published solution), and inverting waveforms just for centroid time and scalar moment (or Mw). These results (Figs. 9–11) showed that the velocity models obtained in this paper are reasonable; more specifically, the Pantanal Basin velocity models are somewhat less reliable than the Offshore event models. The test also explained that some failures of the single-station inversions for Greek event (e.g. in panels A, C and D of Fig. 7) are rather due to ill-posed MT inversion than due to a problematic velocity model.

The specific results of the paper elucidated two focal mechanisms of rare Brazilian events, and validated new path-dependent velocity models. The new methodology of the paper, consisting in combining the dispersion-wave analysis with the waveform inversion, in which each source-station path has its specific model, proved to be a viable tool with broad applicability in regions where only few and relatively distant broad band stations are available, both in Brazil (such as used by Assumpção et al., 2016), or elsewhere. As such, the paper is relevant for seismologist and geologists not only in South America, but also for a broader scientific community. The newly developed inversion tool (the frequency range test) is helpful in recognizing uncertainty of the focal mechanisms.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jsames.2016.07.004>.

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