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Tsunamigenic earthquakes in the Gulf of Cadiz: fault model and recurrence

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Abstract. The Gulf of Cadiz, as part of the Azores-Gibraltar plate boundary, is recognized as a potential source of big earthquakes and tsunamis that may affect the bordering countries, as occurred on 1 November 1755. Preparing for the future, Portugal is establishing a national tsunami warning system in which the threat caused by any large-magnitude earthquake in the area is estimated from a comprehensive database of scenarios. In this paper we summarize the knowledge about the active tectonics in the Gulf of Cadiz and integrate the available seismological information in order to propose the generation model of destructive tsunamis to be applied in tsunami warnings. The fault model derived is then used to estimate the recurrence of large earthquakes using the fault slip rates obtained by Cunha et al. (2012) from thin-sheet neotectonic modelling. Finally we evaluate the consistency of seismicity rates derived from historical and instrumental catalogues with the convergence rates between Eurasia and Nubia given by plate kinematic models.

1 Introduction and geodynamic setting

The Gulf of Cadiz is known to be the source area for the 1 November 1755 destructive earthquake and tsunami that affected Portugal, southwestern Spain and northern Morocco. The magnitude of this event has been estimated to be $M_\mathrm{w} \sim 8.7$ (e.g. Johnston, 1996), and the occurrence of large earthquakes in this area dominate the seismic hazard in the bordering countries (e.g. Jimenez and Garcia-Fernandez, 1999). However, given the very long seismic cycle associated with these extreme events (more than 1000 yr) the uncertainty about the recurrence period for large earthquakes and tsunamis generated offshore is extremely high. The largest instrumental earthquake recorded in the area was on 28 February 1969 ($M_\mathrm{w} = 7.8$; Fukao, 1973), and since 1960 only 19 events have been recorded with $M_\mathrm{w} \geq 5.0$ and two with $M_\mathrm{w} \geq 6.0$.

The quest for the active faults that can generate destructive earthquakes and tsunamis, like that on 1 November 1755, led to a very thorough geological and geophysical investigation of the Gulf of Cadiz. As a result of the extensive multi-beam bathymetric coverage (Zitellini et al., 2009) and numerous high-quality multi-channel seismic surveys, several large faults have been mapped and considered active (Fig. 1). The most prominent active structures are the NNE–SSW to NE–SW trending thrust faults like the Tagus Abyssal Plain Fault (Cunha et al., 2010), the Marquês de Pombal Fault (Zitellini et al., 2001; Terrinha et al., 2003), the Horseshoe Fault (Gràcia et al., 2003; Zitellini et al., 2004), the Gorringe Bank Fault (Hayward et al., 1999) and the Portimão Bank Fault (Baptista et al., 2003). Recently Zitellini et al. (2009) identified a new set of major tectonic lineaments striking WNW-ESE between the western Horseshoe Abyssal Plain and the eastern Gulf of Cadiz (the SWIM lineaments in Fig. 1) that show evidence of recent dextral strike-slip movement (Rosas et al., 2009). According to Zitellini et al. (2009) the SWIM (SouthWest Iberian Margin) lineaments could represent the transition from a diffuse plate boundary (Sartori et al., 1994; Hayward et al., 1999) to a discrete transform fault zone setting.

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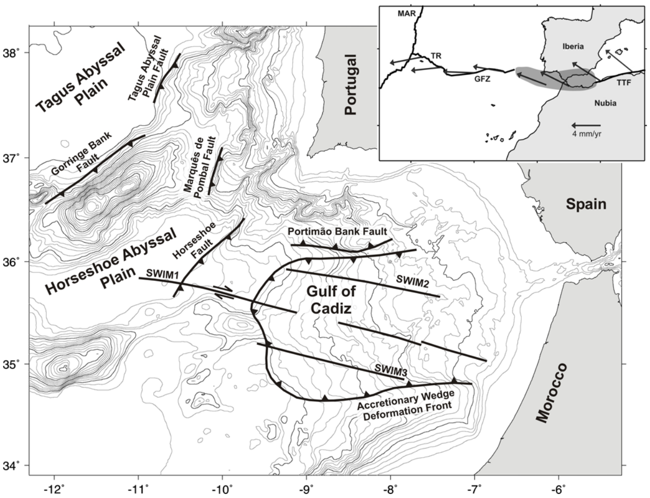

Fig. 1. Simplified tectonic map of the Gulf of Cadiz and neighbouring Abyssal Plains (see text for references). In the background we have the GEBCO (2003) (General Bathymetric Chart of the Oceans) bathymetry with highlighted contours every 1000 m. Inset on the top right corner shows the well-identified segments of the Nubia-Eurasia plate boundary (thick black lines). The shaded area identifies the zone where this plate boundary is less constrained. The arrows show the relative movement of Nubia with respect to Eurasia at distinct locations of the boundary after Fernandes et al. (2003). GFZ – Gloria Fracture Zone; MAR – Mid-Atlantic Ridge; TR – Terceira Ridge; TTF – Tell Thrust Front.

The recent tectonic activity in the Gulf of Cadiz is a consequence of its geodynamic setting, at the eastern end of the Eurasia-Nubia Azores-Gibraltar plate boundary. According to kinematic plate models, based on GPS data, in this region the plate convergence is oblique, striking NW-SE to WNW-ESE, and occurs at a rate of 4.0 to 5.5 mm yr^{-1} (Calais et al., 2003; McClusky et al., 2003; Fernandes et al., 2003; Fig. 1 inset). However, this simple plate kinematic setting is disputed by other authors (Gutscher et al., 2002; Gutscher, 2012), who suggest that another, more powerful tectonic engine is in operation: the E–W subduction roll-back.

It is undeniable that tomographic models clearly image a partially detached slab beneath the Alboran Sea, East of Gibraltar, extending to depths of more than 600 km (e.g. Spakman and Wortel, 2004). The rapid roll-back of this east-dipping subducting slab, compensated by extension in the overriding continental crust, has also been invoked to explain the formation and evolution of the Alboran Domain through the Early and Middle Miocene (Lonergan and White, 1997; Rosenbaum et al., 2002).

The MCS seismic profiles acquired in the Gulf of Cadiz (Medialdea et al., 2004; Thiebot and Gutscher, 2006) image an accretionary wedge (Fig. 1) and show west-vergent thrust faults (not shown in Fig. 1 due to its small scale) soling in depth along an east-dipping décollement that in places offsets the seafloor. However, there is no instrumental seismicity in the central Gulf of Cadiz that can be associated with an active subduction zone. The active subduction zone model of Gutscher et al. (2002) is also inconsistent with the absence of magmatism younger than 6 Ma in the eastern Alboran (see arguments in Platt and Houseman, 2003).

Recently, in an effort to evaluate the likelihood of the different seismotectonic settings proposed for the Gulf of Cadiz, Cunha et al. (2012) applied the thin-sheet modelling methodology developed by Bird (1999) to estimate seismic strain rates, stress orientations, fault slip rates and local velocities that could be compared to observations. These authors observed that the consistency between model and observations indicates that forcing by slab sinking beneath Gibraltar is not required to reproduce current horizontal deformation in these areas. Furthermore, in accordance with geological and GPS observations, the Nubia-Eurasia convergence is accommodated partially in NW Morocco and partially in the Gulf of Cadiz over an area $>$ 200 km wide. Other consequences of the modelling results by Cunha et al. (2012) were that the SWIM lineaments do not represent a mature fracture zone cutting through the whole lithosphere and that the long-term average fault-slip rates on the major thrust faults ranges between 1 to 2 mm yr^{-1}.

Whatever main active tectonic engine is at work in the Gulf of Cadiz, this area is recognized as the major source of large earthquakes that can generate destructive tsunamis that affect the whole North-East Atlantic. Recognizing this, Portugal has been developing a Tsunami Warning System (the PtTWS) following the recommendations issued by the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS).

The PtTWS is the responsibility of the Instituto Português do Mar e da Atmosfera, I.P. (IPMA), which is the national institution operating on a 24-7 basis that is responsible for the Portuguese seismic network. Starting from a seismic detection, the operator evaluates the tsunami threat level to the coastal areas and issues appropriate messages to the Portuguese Civil Protection. After receiving information on the sea level, the tsunami threat is re-evaluated and messages are updated accordingly (see Annunziato et al., 2009 for more details). One critical component of the PtTWS is the tsunami scenario database and the Tsunami Analysis Tool that help the operator to make decisions during the course of the event.

The ultimate goal of any Tsunami Warning System is to provide the coastal areas that may be affected by a tsunami with an accurate forecast of the inundation level to be expected. Recent advances in computing performance and an increase in sea level observations make this objective attainable for trans-oceanic events that can take hours to reach the coast (Titov, 2009). For faraway sources, the details on the seismic rupture can be neglected and a simplified fault model can be applied (ibid.). This fault model is then inferred in real time using the sea level observations in deep-ocean.

Successful examples of tsunami forecast are given by Wei et al. (2008) and Tang et al. (2012).

However, when the deep-ocean monitoring system is incomplete or when the arrival time of the tsunami is very short (the case of near-shore sources), then the level of alert that should be applied to a particular stretch of the coast is estimated using pre-computed tsunami scenarios (e.g. Greenslade et al., 2007 for the Indian Ocean; Kamigaichi, 2011 for Japan; Steinmetz et al., 2010 for near field tsunamis affecting Indonesia). A tsunami scenario is a single-model run that is calculated ahead of time with the initial conditions carefully selected so that they are likely to represent an actual tsunamigenic earthquake (Greenslade and Titov, 2008).

In Japan, where tsunamis can hit the coast in just a few minutes, more than 64 000 tsunami scenarios were computed for different sets of location, magnitude and top of the fault depth. Close to the coastline the tsunamigenic earthquakes are modelled in a grid 0.5° × 0.5° while for more distant sources the grid spacing is increased to 1° × 1° (Kamigaichi, 2011). For the sake of the early warning, the most efficient tsunami generation is considered for the source faults (rake = 90° and dip = 45°) when the average tectonic setting is not well constrained from past earthquakes in the region (ibid.).

This paper describes the work done to generate the basic set of tsunami sources that populate the tsunami scenario database for the Gulf of Cadiz, taking into consideration the most updated seismotectonic knowledge.

Later on, we will estimate the recurrence of large earthquakes in the area using the fault slip-rates inferred from the thin-sheet neotectonic modelling of Cunha et al. (2012), Finally, we will explore the derived model to evaluate the consistency of seismicity rates computed from historical and instrumental catalogues with the convergence rates between Eurasia and Nubia given by plate kinematic models. The generation model presented may have other future applications, such as for Probabilistic Seismic Hazard Assessment, for Probabilistic Tsunami Hazard Assessment or for the computation of synthetic strong motion records (like in Carvalho et al., 2008).

2 The tsunami generation model

In this work we consider that tsunamis are generated by deformation of the sea-bottom caused by an earthquake that is communicated without attenuation to the sea surface. By doing this we are disregarding the filtering effect of the water layer or the effects of the horizontal motion on a irregular seafloor topography (effects discussed by Nosov and Kolesov, 2011) which is a common approach used in the generation of scenario databases.

As the details of the fault rupture are difficult to assess or predict in the Gulf of Cadiz area, we adopt the elastic deformation model of Okada (1985) to determine the shape of the initial vertical displacement. This model assumes that the rupture occurs by a uniform slip on a rectangular fault plane (Fig. 2) and it is widely used in tsunami scenarios for warning systems worldwide (e.g. Gica et al., 2008; Kamigaichi, 2011). Fault sources with non-uniform slip distributions are used for instance in the GITEWS (German Indonesian Tsunami Early Warning System) (Babeyko et al., 2010).

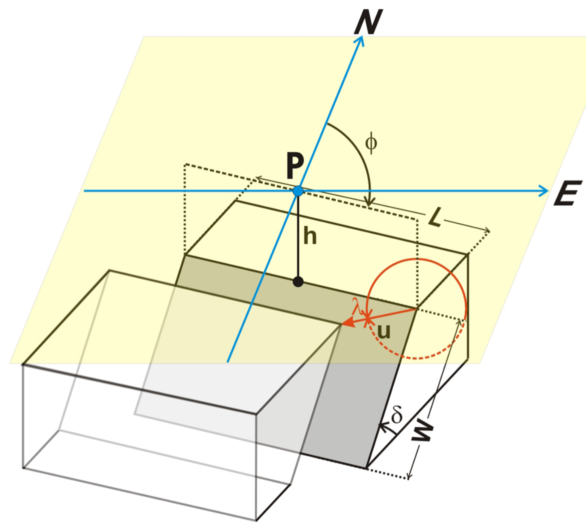

Fig. 2. Main parameters required to define the fault rupture that causes a tsunami, using the Okada (1985) elastic dislocation model.

At each surface location point P (considered as the centre of the top of the fault line) and for each value of moment magnitude M_w, the complete definition of an Okada source model requires the following seven parameters (Fig. 2):

- Fault width W
- Fault length L
- Fault dip δ
- Fault azimuth (strike) φ
- Depth below seafloor h
- Average slip along the fault u
- Slip angle (rake) λ

The shape and amplitude of the surface displacement of the medium depends also on some material properties like the shear modulus μ and the Poisson's ratio σ, increasing the number of parameters to nine. The shear modulus is also important in the definition of seismic moment

$$M_0 = \mu A u, \quad (1)$$

where A is the fault area ($A = WL$). The moment magnitude M_W is linked to the seismic moment M_0 through

$$M_W = \frac{\log M_0}{1.5} - 6.07, \quad M_0 \text{ in Nm.} \quad (2)$$

From this list of nine parameters, we may fix only two from the start, the depth below the seafloor and the Poisson's ratio. We will consider that the tsunami warning system will initially work based on the worst-case scenario and thus fix the top-of-the-fault depth below the seafloor to 5 km. We assume a Poisson's ratio of 0.25, which is an approximate value that is common to many rocks in the crust and mantle where the seismic velocities obey the relationship $V_P \approx \sqrt{3} V_S$. All the other seven parameters have to be defined for each location and each magnitude:

$$W \quad L \quad \delta \quad \varphi \quad u \quad \lambda \quad \mu$$

The independent variables are the geographical location $\boldsymbol{r}$ (that is linked to the tectonic setting along the Azores-Gibraltar plate boundary) and the moment magnitude M_W. To facilitate the discussion we group the parameters in terms of their dependence to these variables. First, the strike, dip and rake of the fault, and the shear modulus, depend only on location, not magnitude. They result from the choice of the fault (Fig. 1) that best represents the geological setting of that particular location:

$$\delta(\boldsymbol{r})\varphi(\boldsymbol{r})\ \lambda\ (\boldsymbol{r})\ \mu(\boldsymbol{r})$$

The length, width and slip of the fault depend both on location and on magnitude:

$$W(\boldsymbol{r}, M_W) L(\boldsymbol{r}, M_W) u(\boldsymbol{r}, M_W)$$

In the next sections we will address the approaches used to compute each one of these parameters.

3 Tsunami generation source areas

We begin by dividing the Gulf of Cadiz area and neighbouring Abyssal Plains into domains where a single fault model can be considered as typical and credible. We took into consideration the most recent geological and geophysical investigations in the area (see Introduction and Fig. 1) to define nine different generation scenarios as indicated in Fig. 3, named from GC01 to GC09. A simple comparison with Fig. 1 shows that each source region can be identified with a major active thrust fault, with the exception of zones GC02, GC06 and GC07. We note that for the sake of completeness we do not discard the subduction slab roll-back as a possible cause of large earthquakes and tsunamis (zone GC09). As a tsunamigenic fault the definition of this zone follows very closely the one that was proposed by Gutscher et al. (2006).

Source zone GC02 represents the blind thrust fault that has been hypothesized by Terrinha et al. (2003), and it is included to provide a complete coverage of the offshore area with possible tsunamigenic sources. The same effort of completeness justifies the consideration of source zone GC06 (the Guadalquivir Bank). Here a prominent bathymetric feature is

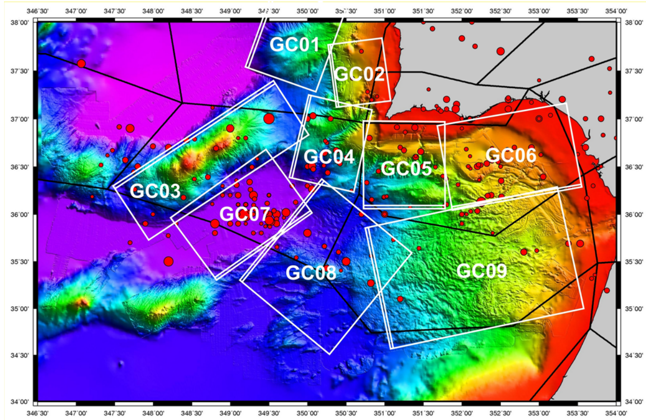

Fig. 3. Main tsunami source areas to be considered in the Gulf of Cadiz (in white). Each rectangle represents a pure thrust fault with the double trace indicating the shallow trace of the fault. For comparison we show in black the seismic zones recently proposed by the SHARE (Seismic Hazard Harmonization in Europe) project (2012) to be considered for Probabilistic Earthquake Hazard Assessment. The red circles show the instrumental seismicity for $M > 4$. The data sources are detailed in Sect. 7 of the main text.

associated with a diffuse seismic activity, but MCS lines have failed to identify a clear large thrust fault (e.g. Medialdea et al., 2004). Given this uncertainty we consider that GC06 represents a tectonic source similar to the Portimão Bank Fault (Fig. 1 and zone GC05 in Fig. 3).

The zone GC07 was introduced to consider the tectonic source that was responsible for the 28 February 1969 $M_w = 7.8$ earthquake. In fact, despite the many research cruises conducted in the area (e.g. Bartolome, 2012), the fault that is responsible for such a large earthquake has yet to be identified. In the area a thick sedimentary layer is found (ibid.), and the fault may not have ruptured to the surface. We adopted for this zone the orientation given by one of the fault planes as computed by Fukao (1973).

The definition of source zones provided in Fig. 3 defines the strike of each fault, $\varphi(\boldsymbol{r})$, to be considered in the tsunami generation scenarios. As we consider the worst case possible for the tsunami generation, we assume that all faults are pure dip-slip thrusts and so the rake of the scenarios is fixed to $\lambda(\boldsymbol{r}) = 90°$. Next we provide the rationale for the definition of the scenario fault dip by computing the optimum and maximum allowed angles for this type of fault.

The friction on a plane between two surfaces is given by the Amonton's law

$$\tau = \mu_F (\sigma_n - p_f), \tag{3}$$

where τ is the shear traction, σ_n is the normal stress, p_f is the pore pressure and μ_F is the coefficient of friction. Byerlee (1978) showed that this law is obeyed for all types of rocks with a near-constant friction, $\mu_F = 0.6$ to 0.85. The fault planes on which slip can occur with the minimum possible effective stress, $\sigma_n - p_f$, are the planes inclined at angles θ_{opt} to σ_1, such that

$$\tan 2\theta_{opt} = \pm \frac{1}{\mu_F} \quad \text{or} \quad \theta_{opt} = \frac{1}{2}\tan^{-1}\left(\frac{1}{\mu_F}\right). \tag{4}$$

For a pure dip-slip thrust fault the principal compressive stress is horizontal so that this expression gives the optimal dip angle for such a fault. However, not all angles are allowed for a thrust fault. In fact, there is a maximum value of θ beyond which slip cannot occur for any combination of positive stresses (Sibson, 1985). The maximum angle, θ_{lu}, is known as the lock-up angle. It can be deduced that this angle is given by

$$\theta_{lu} = \tan^{-1}\left(\frac{1}{\mu_F}\right) = 2\theta_{opt}. \tag{5}$$

Using this equation we deduce that when the friction coefficient increases from 0.60 to 0.85, the optimum fault dip angle decreases from 29.5° to 24.8° and the lock-up fault dip angle decreases from 59.0° to 49.6°.

If we consider the 28 February 1969 $M_w = 7.8$ earthquake in the area as a reference for the Gulf of Cadiz, then we should assume that $\delta = 50°$ is the typical dip for the thrust faults in the area, following the Fukao (1973) fault plane solution. This value is very close to the lock-up angle, and it should be considered with caution. Authors who have proposed source models for the 1755 earthquake suggested smaller dip angles, 40° (Johnston, 1996) or 45° (Ribeiro et al., 2006). In this work, for a pure dip-slip thrust fault, we will assume for the dip, $\delta(\boldsymbol{r})$, a more conservative value of 35°, closer to the optimum values computed above. This value applies to all the source zones defined, except for zone GC09 which represents the Gulf of Cadiz subduction slab roll-back. For this zone we assume that the fault tip is 5°, in line with what has been proposed by Gutscher et al. (2006) and in line with the cartography of the basement and crust presented by Thiebot et al. (2006).

4 Seismogenic thickness of the lithosphere

When the dip of a rectangular fault $\delta(\boldsymbol{r})$ is known, its maximum width is given as a function of the seismogenic thickness Z_{seis} by

$$W_{max} = \frac{Z_{Seis}}{\sin(\delta)}. \tag{6}$$

In the Gulf of Cadiz area, earthquakes that have a well-constrained focal depth (Enghdal et al., 1998; Stich et al., 2007; Geissler et al., 2010) show that moderate events can be generated at depths attaining 30 to 60 km. We must therefore consider that the top of the lithospheric mantle is brittle, in line with some rheological models proposed for the area (Neves and Neves 2009; Cunha et al., 2010).

The Gulf of Cadiz area and surrounding Abyssal Plain is underlain by thinned continental and/or transitional or oceanic type crust of the Jurassic age (Gonzalez et al., 1996, 2001; Rovere et al., 2004; Afilhado et al., 2008; Sallares et al., 2011). If we accept that the maximum hypocenter depth of small earthquakes defines the base of the seismogenic lithosphere, then 60 km is 5 to 10 km deeper than what is expected from thermal models of a cooling oceanic lithosphere (e.g. McKenzie et al., 2005). We ascribe the difference to the fact that in this region the lithosphere does not have a generalized typical oceanic nature, except maybe for some localized domains. Considering that the rupture of very large earthquakes can extend into the ductile lithosphere (e.g. Scholz, 1988), we will adopt in our fault model that the maximum lithosphere rupture depth is 70 km. As a consequence, the maximum width we consider for a fault is 120 km.

The nature and seismogenic thickness of the lithosphere also provides the constraints needed to define the shear modulus we may use for the fault model. As $\mu = \rho\, V_S^2$, Stich et al. (2007) proposed to use $\mu = 7.0 \times 10^{10}$ Pa for the oceanic lithospheric mantle, while a value of $\mu = 4.0 \times 10^{10}$ Pa is more adequate for a rupture occurring in the crust. In this work, as we consider that the faults also rupture the top crustal layer of the lithosphere, we will assume for the brittle lithosphere the value $\mu = 6.5 \times 10^{10}$ Pa, identical to the one used by Johnston (1996). For the subduction slab roll-back source area (GC09), we will consider the shear modulus adequate for a crustal rupture given above.

This value can be considered excessive for zones like GC02, GC04 or GC06 (Fig. 1) where the top of the fault trace is located in areas with thinned continental crust, ranging from 10 to 15 or 20 km thickness, respectively (Gonzalez et al., 1996, 2001; Rovere et al., 2004; Thiebot and Gutscher, 2006; Afilhado et al., 2008; Sallares et al., 2011). Allowing for a fault extending up to 5 km below seafloor we see that for the smaller magnitude events ($6.5 \leq M \leq 7.0$) a significant part of the rupture occurs in continental crust. The consequences of using a larger rigidity for these scenarios, is equivalent to an overestimation of 0.1 in the moment magnitude. This is the typical uncertainty in magnitude estimates. However, in the Portuguese tsunami warning system, the operator may need to take this difference into consideration when selecting the best tsunami scenario for a given observed moment magnitude.

5 Fault-slip versus earthquake size relationship

After the discussion of the tsunami source model done in the previous paragraphs, we are left with only three parameters to define as a function of magnitude and location: the fault length, fault width and average slip. In earthquake and tsunami hazard studies it is common to use empirical compilations from global earthquake databases, such as the ones found in Wells and Coppersmith (1994) or Stirling et al. (2002). These empirical relationships that relate fault slip with magnitude or one fault dimension are usually grouped by fault type or by tectonic environment. However, we will not use them in this study.

As we have seen above, the Gulf of Cadiz and neighbouring Abyssal Plains comprise a very peculiar geodynamic setting that is not found anywhere else on Earth. Here we find that the crust is very heterogeneous, with domains of thinned continental crust, exhumed mantle, atypical thin oceanic crust, and oceanic crust formed in a slow spreading or transform setting (Gonzalez et al., 1996, 2001; Rovere et al., 2004; Afilhado et al., 2008; Sallares et al., 2011). The oceanic-like lithosphere is one of the oldest found on Earth (Jurassic), with a very thick brittle layer (~ 60 km), and it is today submitted to a slow oblique convergence at a rate of $\sim 4\,\mathrm{mm\,yr^{-1}}$. The global earthquake databases that are the base of the published empirical laws are dominated by events in the most active tectonic environments that we do not consider representative of the Gulf of Cadiz region.

Given this, we prefer to use a semi-empirical model for the relationship between fault-slip and earthquake size or fault dimensions along the lines of the work of Scholz (1982) and Manighetti et al. (2007). The semi-empirical scaling law that we propose takes the shape of the law put forward by Manighetti et al. (2007):

$$D_{\max} \rightarrow \begin{cases} L \leq 2W_{\mathrm{Sat}} & D_{\max} = \alpha \frac{L}{2} \\ L > 2W_{\mathrm{Sat}} & D_{\max} = \alpha \frac{1}{\frac{1}{L} + \frac{1}{2W_{\mathrm{Sat}}}} \end{cases} . \quad (7)$$

Here $D_{\max}$ is the maximum displacement on the fault, L is the fault length and W_{Sat} is the saturation width, which we assimilate to the maximum rupture thickness discussed above. We will also assume that $D_{\max} = 2D (= 2u)$ as in Manighetti et al. (2007).

The analysis of this type of scaling law was performed by Manighetti et al. (2007) using a new compilation of $D_{\max}(L)$ data that expanded previous compilations like the one by Wells and Coppersmith (1994). Making a systematic search on the parameter space for the scaling law above (α, W_{Sat}), these authors proposed four typical laws (coloured lines in Fig. 4) that fit two observations data sets, one generated by surface evaluation and the other by inversion at depth (ibid.).

For the Gulf of Cadiz-SW Iberia area, we estimated the scaling law parameters from the few available constrains on large earthquakes in the area, namely (yellow stars in Fig. 4): (1) the one on 28 February 1969; (2) the one on 12 February 2007 and (3) the historical 1755 earthquake and tsunami (cluster of stars at the top right side of the graphic in Fig. 4).

The 28 February 1969 event was the largest instrumental earthquake recorded in the region, with an estimated magnitude of $M_{\mathrm{w}} = 7.8$. This earthquake generated a small tsunami that was recorded by tide gauges around the Gulf of Cadiz and has been studied by several authors (e.g. Gjevik et al., 1997). The preferred model for the tsunami generation

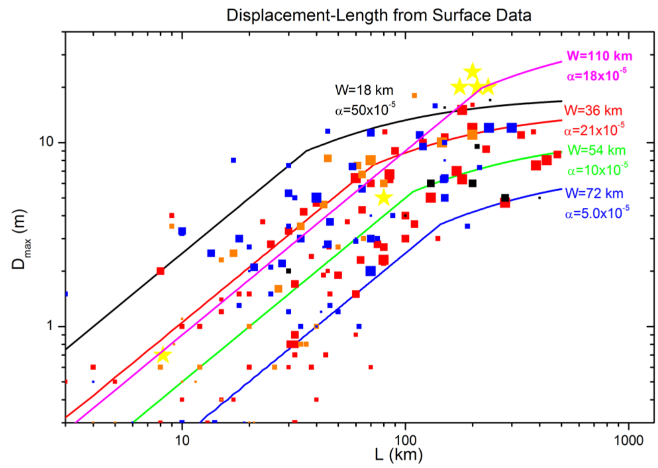

Fig. 4. Maximum displacement versus fault length derived from surface measurements (adapted from Manighetti et al., 2007): red squares, strike-slip events; orange squares, dip-slip events; blue squares, composite faults. The black squares were not used in the regression analysis. The size of the symbols is proportional to the quality of data. Also represented are the four typical laws selected by the automatic regression of Manighetti et al. (2007; coloured lines). The data points from the Gulf of Cadiz are plotted as yellow stars, and the magenta line depicts the adopted scaling law (see text for details).

was based on the Fukao (1973) focal mechanism, which assumes a fault striking N55° E, parallel to the Gorringe Bank, 80 km long and 50 km wide. The fault area was estimated by Fukao (1973) using the distribution of aftershocks, and so it must be considered with some caution, giving the large uncertainty in their location with the seismic network of the time.

The 12 February 2007 earthquake was investigated by Stich et al. (2007) using modern waveform inversion techniques. Its magnitude was $M_{\mathrm{w}} = 6.0$ and the fault area (assumed circular) was estimated to be $54\,\mathrm{km}^2$. The calculated average slip is $D = 0.34$ m, and an equivalent length and width can be estimated to be $L = 8.2$ km and $W = 6.5$ km, respectively. The same event was also investigated by Buforn et al. (2007), who produced other estimates for the size of the fault, $L = 14$ km and $W = 12.5$ km. For these authors the magnitude is slightly smaller, $M_{\mathrm{W}} = 5.9$ and, consequently, the inferred average slip was calculated to be $D = 0.07$ m, i.e. much smaller than that given by Stich et al. (2007).

Regarding the 1755 earthquake and tsunami, we will examine here only the proposals made by Johnston (1996) and Ribeiro et al. (2006). These authors proposed a source at the Gorringe Bank (GB), the Horseshoe fault (HSF) and the Marquês de Pombal fault (MPF), and a composite of the previous two (HSF + MPF). The main parameters are summarized in Table 1.

The comparison of the proposed source models for the 1755 earthquake with the Manighetti et al. (2007) reference

Table 1. Proposed source parameters for the 1755 earthquake ($\mu = 6.5 \times 10^{10}$ Pa). The source parameters indicated as "Ribeiro*" represent a modification of the Ribeiro et al. (2006) proposal, taking into consideration a slight decrease in the maximum seismic rupture allowed.

Author	Fault	L (km)	W (km)	A (km^2)	u (m)	M_0 (Nm)	M_W	δ
Ribeiro	HS	175	140	24 500	10	1.59×10^{22}	8.74	45
Ribeiro	MP	60	120	7212	10	4.69×10^{21}	8.39	30
Ribeiro	HS+MP	235		31 712	10	2.06×10^{22}	8.82	45
Johnston	GB	200	80	16 000	12.1	1.26×10^{22}	8.67	40
Ribeiro*	HS	150	120	18 031	10	1.17×10^{22}	8.65	45
Ribeiro*	MP	60	120	7212	10	4.69×10^{21}	8.39	45
Ribeiro*	HS+MP	210	120	25 200	10	1.64×10^{22}	8.75	45

data set shows that the maximum slip predicted for the 1755 event clearly exceeds what is normally observed from surface data or waveform inversion (Fig. 4). We must note, however, that Manighetti et al. (2007) considered in their study only earthquakes with a fault width of $W < 40$ km. This restriction, in light of the tectonic environment in the Gulf of Cadiz-SW Iberia region, is not appropriate. The recent 11 March Japan earthquake, with maximum co-seismic slip reaching close to 30 m (e.g. Ozawa et al., 2011), shows that the empirical relationships proposed by Manighetti et al. (2007) do not have a generalized application and seem to fail for large-width source faults.

Our proposal, for the scaling law between maximum displacement and fault length using the equation of Manighetti et al. (2007), depicted above, assumes $\alpha = 18 \times 10^{-5}$ and $W_{\mathrm{Sat}} = 110$ km. This law is represented by the magenta curve in Fig. 4, where the value proposed for W_{Sat} is very close to the maximum allowed fault width. The relationship between fault-slip and moment magnitude follows from the previous equations and the relationship between moment magnitude and seismic moment. The width of the fault for a given length was estimated using an aspect ratio (L/W) of 1.2 which seems to fit the scarce information available in the Gulf of Cadiz. A summary of our proposed model for the generation of large earthquakes (and tsunamis) in the Gulf of Cadiz is presented in Table 2, for magnitudes $M_W \geq 7$. This table applies to all source zones defined, except for zone GC09, which comprises the subduction slab roll-back tectonic setting. For future reference we identify this scaling law as WLU-1.

As zone GC09 is considered to represent a subduction zone and this type of tectonic environment is well represented in global earthquake compilations, we propose to use a different approach in this case. We begin by considering the empirical law of Ward (2001) for tsunami sources, as it was used by Annunziato et al. (2007) in the establishment of a global database of tsunami scenarios,

$$\log(L) = 0.5M_W - 1.8. \quad (8)$$

Next, we consider that the fault width is 28 % of its length (as suggested by global compilations of earthquake sources, e.g. Stirling et al., 2002 for $M > 6.5$), which translates to

$$\log(W) = 0.5M_W - 2.353. \quad (9)$$

Table 2. Main parameters for the WLU-1 model of large earthquake generation in the Gulf of Cadiz-SW Iberia region. This model applies to all zones except GC09.

M_W	M_0 (Nm)	L (km)	W (km)	u (m)
7.00	4.03×10^{19}	25	21	1.15
7.25	9.55×10^{19}	34	28	1.53
7.50	2.26×10^{20}	45	38	2.04
7.75	5.37×10^{20}	60	50	2.72
8.00	1.27×10^{21}	81	67	3.62
8.25	3.02×10^{21}	107	89	4.83
8.50	7.16×10^{21}	143	119	6.44
8.75	1.70×10^{22}	220	120	9.90

Finally, we use the relationship between seismic moment and moment magnitude to derive the average displacement along the fault. This model is presented in Table 3 and is identified as WLU-2. Equation (8) is the one used in Japan for the generation of the tsunami database of scenarios (Kamigaichi, 2011), but they consider that the fault length is typically 50 % of the fault width so that the constant term in Eq. (9) is changed to 3.3 (ibid.)

If we compare the adopted scaling law with the data compiled by Stirling et al. (2002), we find a very good fit that supports our choice for zone GC09 (see Supplement, Figs. S1 and S2). We summarize all of the properties discussed previously for each source zone in the Gulf of Cadiz in Table 4.

Using the empirical relationships proposed by Kanamori and Anderson (1975), we conclude that both WLU-1 and WLU-2 are near constant stress drop fault models. While the stress drop for the WLU-2 model (Gulf of Cadiz subduction zone) is equal to 14 bar for all magnitudes, the stress drop for the WLU-1 model is equal to 32 bar for the smaller magnitudes and increases to an average 40 bars for magnitudes equal to or above 8.25. As could be expected, the stress drop inferred from the WLU-2 model is typical of "inter-plate"

Table 3. Main parameters for the WLU-2 model of large earthquake generation in the Gulf of Cadiz-SW Iberia region. This model applies only to zone GC09.

M_w	M_0 (Nm)	L (km)	W (km)	u (m)
7.00	4.03×10^{19}	50	14	1.38
7.25	9.55×10^{19}	67	19	1.84
7.50	2.26×10^{20}	89	25	2.46
7.75	5.37×10^{20}	119	33	3.28
8.00	1.27×10^{21}	158	44	4.37
8.25	3.02×10^{21}	211	59	5.83
8.50	7.16×10^{21}	282	79	7.78
8.75	1.70×10^{22}	376	105	10.4

Table 4. Summary of properties for the Gulf of Cadiz tsunamigenic source zones.

Zone	Rake (λ)	Dip (δ)	Shear Modulus (μ) Pa	Strike (φ)	$W-L-u$
GC01	90°	35°	6.5×10^{10}	30°	WLU-1
GC02	90°	35°	6.5×10^{10}	−7°	WLU-1
GC03	90°	35°	6.5×10^{10}	57°	WLU-1
GC04	90°	35°	6.5×10^{10}	23°	WLU-1
GC05	90°	35°	6.5×10^{10}	−90°	WLU-1
GC06	90°	35°	6.5×10^{10}	−100°	WLU-1
GC07	90°	35°	6.5×10^{10}	−125°	WLU-1
GC08	90°	35°	6.5×10^{10}	39°	WLU-1
GC09	90°	5°	4.0×10^{10}	−11°	WLU-2

earthquakes, while the higher value inferred from the WLU-1 model is closer to the "intra-plate" earthquakes, as defined by Kanamori and Anderson (1975).

6 Implications for the recurrence of large earthquakes and tsunamis

In this section we use our model for the generation of large earthquakes in the Gulf of Cadiz, together with the long-term average fault slip-rates recently computed by Cunha et al. (2012), to estimate the recurrence period of large seismic events in the Gulf of Cadiz. For simplicity we will assume the "characteristic earthquake" model for event generation. This model assumes that all strain is released on the fault during extreme events. As the partial release of seismic strain during smaller earthquakes will increase the recurrence period of large earthquakes, the values obtained using this approach should be considered as the shortest estimate, or the lower bound.

If we know the slip that occurs during a large earthquake of magnitude M_w, $D(M)$, then the recurrence period, T_R, of a fault with slip-rate V_F is easily computed by:

$$T_R = D(M)/V_F. \quad (10)$$

According to the best-fit neotectonic model put forward by Cunha et al. (2012), characterized by strain partitioning over a region > 300 km wide, predicted fault slip-rates are up to 1.5 mm yr^{-1} along the NE–SW Guadalquivir thrust fault, in the northern Gulf of Cadiz, and between 0.5 and 1 mm yr^{-1} thrusting in the NNE–SSW to NE–SW trending thrust faults off SW Portugal.

As the longest, spatially continuous fault segment which has been mapped in the region is ∼ 120 km (Horseshoe Fault), and other major faults do not exceed 80 to 100 km (Gràcia et al., 2003; Zitellini et al., 2004; Terrinha et al., 2009), the maximum expected magnitude from our proposed rupture model is between 8 and 8.3 (Table 4, for the non-subduction source zones). For a $M_w = 8$ event, for example, recurrence periods between 3600 and 7200 yr are expected, approximately, on a single fault. The occurrence of a "1755-like" earthquake of magnitude $M_w \sim 8.7$ implies the co-seismic rupture of several faults and, for an average slip rate of 1 mm yr^{-1}, the estimated recurrence period of such an extreme event is circa-10 000 yr.

These estimates of the recurrence period of large earthquakes apply to a single structure or association of structures. As we have seen, there are several major active faults in the Gulf of Cadiz that can generate magnitude 8 earthquakes (at least five mapped thrusts off SW Iberia), and at least three compound sources have been proposed to generate a new "1755-like" earthquake and tsunami. Considering the long-term average fault slip rates, we can estimate that a magnitude 8 event in the Gulf of Cadiz may occur every 700 hundred years and an extreme event with a magnitude of ∼ 8.7 may occur every 3500 yr or less. However, given their geographical proximity, it is likely that these large structures will interact and large earthquakes may happen clustered in time.

7 Comparison between earthquake strain release and plate kinematics

We have seen that the seismicity in the Gulf of Cadiz and adjacent Abyssal Plains dominates the seismic (and tsunami) hazard estimated for the neighbouring countries, Portugal mainland, SW Spain and NW Morocco. In these countries the building codes for earthquake resistance are based on studies that use the Probabilistic Seismic Hazard Assessment methodology (PSHA) as introduced initially by Cornell (1968) and later developed by McGuire (1977) (see Sousa and Costa, 2009, for the case of Portugal). Given the very long recurrence of large events in this area, the earthquakes are considered to be independent in time and their magnitude-frequency distribution has to be inferred from historical and instrumental catalogues which are either incomplete or do not cover a complete earthquake cycle. Our proposed rupture model for the generation of large events in the Gulf of Cadiz area provides the parameters needed to compare the recurrence models used in PSHA with the plate tectonic engine, the relative convergence between Nubia and Eurasia. This consistency test is often neglected in the applications of PSHA in Iberia (e.g. Jiménez and García-Fernández, 1999; Vilanova and Fonseca, 2007) with the consequence that the seismicity rate is grossly overestimated or underestimated in the considered source zones.

Besides providing a consistency check, the source models presented in this work can be directly applied to the studies of Probabilistic Tsunami Hazard Assessment (PTHA). This type of studies is much less common than PSHA but their number is likely to increase as authorities and stakeholders are more aware of coastal hazards. Recent examples of PTHA can be found in Gonzalez et al. (2009) for the Pacific Ocean and in Sørensen et al. (2012) for the Mediterranean Sea.

To estimate the frequency–magnitude relationship we use a catalogue that results from the compilation of historical and instrumental earthquakes up to 1969 (Martins and Mendes-Victor, 1999), expanded with the revised instrumental catalogue of Carrilho et al. (2004) up to 2000 and complemented with the bulletins published online by the Instituto Português do Mar e da Atmosfera, I.P. (Supplement, Fig. S3). We began by examining the catalogue in terms of the cumulated number of events (Supplement, Fig. S4), after removing aftershocks and precursors, which allowed us to identify four periods, one historical and three instrumental: Historical: [−33–1909]; Instrumental-1: [1910–1974]; Instrumental-2: [1975–1995]; Instrumental-3: [1996–2011].

Next, we used ZMAP (Wiemer, 2001) to obtain the completeness magnitude and Gutenberg-Richter parameters for each of the 3 instrumental periods (Supplement, Fig. S5). Finally, we use the Bayesian method of Kijko and Sellevoll (1992) to derive the earthquake frequency as a function of magnitude (Supplement, Fig. S6). This method has the advantage of simultaneously considering the information provided by the historical catalogue (each event is considered the maximum event occurring in one time interval) and several periods of instrumental catalogues that are considered complete above the completeness magnitude. The magnitude–frequency relationship is expressed as a truncated Gutenberg-Richter for λ_m, the annual frequency of events that exceeds the magnitude m

$$\lambda_m = \lambda \frac{e^{-\beta(m-m_{\min})} - e^{-\beta(m_{\max}-m_{\min})}}{1 - e^{-\beta(m_{\max}-m_{\min})}} \quad , \tag{11}$$

with

$$\lambda = 88.93 \quad \beta = 2.29 \quad m_{\min} = 1.9 \quad m_{\max} = 8.9. \tag{12}$$

For easier reference we express the recurrence of big earthquakes as the expected number of events over a period of 1000 yr in Table 5.

To compare the magnitude frequency law derived above with the plate tectonic constrain, we will consider a very simple model in which all the seismic energy in the Gulf of Cadiz (Supplement, Fig. S7) is released on a single fault, 500 km long and extending to 70 km in depth (as we proposed for all the source zones excluding GC09). Using this model, the average slip on the fault can be computed by summing the moment released by all possible earthquakes as

$$\Delta \dot{u} = \sum M_0/\mu AT. \tag{13}$$

If we consider the dip we proposed for the thrust fault model we can estimate the seismic velocity as

$$\Delta \dot{u}_S = \frac{\sum M_0}{\mu LWT} \sin 35^\circ \cos 35^\circ \;\rightarrow\; \Delta \dot{u}_S \approx \frac{1}{2}\frac{\sum M_0}{\mu LWT}. \tag{14}$$

Using this expression we obtain 3.6 mm yr^{-1} for the seismic velocity, in good agreement with the current kinematic models that estimate the Nubia-Eurasia convergence to be 4 to 5 mm yr^{-1}.

8 Discussion and conclusions

We derived an earthquake and tsunami generation model for the Gulf of Cadiz-SW Iberia region that allows the computation of a tsunami scenario database to be used in the future Portuguese Tsunami Warning System for the fast appraisal of the impact of an event. We foresee that studies in Probabilistic Seismic Hazard Assessment, Probabilistic Tsunami Hazard Assessment or the derivation of synthetic strong motion records for seismic engineering purposes will also benefit from the results presented.

The proposed model was constructed from the worst-case approach that selected the fault rupture parameters that most affected the initial displacement of the seafloor caused by an earthquake, constrained by the geological and geophysical information available. This means that other choices in the definition of the model, like non-uniform slip distribution or rigidity values, may cause for some events in some coastal zones tsunami waves larger than the ones predicted by our scenario database. The reasons for the choices done were addressed in the previous sections.

One parameter that significantly affects the initial tsunami wave amplitude is the fault dip, being 45° the optimal value, as in Kamigaichi (2011) for the Japanese Tsunami Warning System. In the Indian and Pacific Oceans, the tsunami warning and forecast systems rely on the knowledge of the subduction zones and use non-optimal values but geologically constrained (Greenslade et al., 2007; Titov, 2009; Babeyko et al., 2010). In the Gulf of Cadiz the deep expression of the major geological faults recognized close to the surface in the sedimentary layer (Fig. 1, Sect. 1) is largely unknown. The instrumental seismicity of moderate magnitude ($4 < M < 6$) recorded in the area has no clear connection with the major geological features identified (e.g. Geissler et al., 2010). The major differences between the optimal value and the 35°

Table 5. Frequency of events (in 1000 yr) for a magnitude equal to or exceeding the tabulated value.

M_w	7.00	7.25	7.50	7.75	8.00	8.25	8.50	8.75
Frequency (1000 yr)	9.28	6.52	4.64	3.31	2.39	1.73	1.26	0.82

used for the fault dip in most of the source zones considered are: (i) 45° is very close to the locking angle for a pure dip-slip fault; (ii) 45° would imply for a 1755-like rupture a fault plane extending to 90 km depth or a fault width exceeding the maximum seismogenic thickness (Sect. 4) that is recognized by geological and geophysical investigations. With so few constrains, between a pure "blind" choice or a choice guided by the few information available, we decided for the non-optimal value of 35°.

The operational worst-case scenario proposed here, conservative by nature, will serve as the basis of the first tsunami alert message to be issued by the future PtTWS in case of a large enough event (at this time only earthquake information is usually available). As in any other TWS, the following messages issued by the PtTWS will include information on sea level measurements that will allow confirmation of the occurrence of the tsunami, its cancellation or a change of the warning level. We foresee that the operator, facing a difference in amplitude between observations and the selected scenario, will apply an empirical correction factor to account for differences in the top-of-the-fault depth or in the rake of the rupture mechanism to obtain new estimates for the tsunami wave amplitude arriving at the coast.

Using the most updated geological and geophysical knowledge of the Gulf of Cadiz and adjacent Abyssal Plains, we covered the whole offshore area with zones where a typical credible fault could be identified. We considered that two tectonic engines can be in operation today in this region and did not discard any source of large earthquakes and tsunamis that has been proposed. However, if a probabilistic tsunami hazard assessment is desired (PTHA) (as in Gonzalez et al., 2009 for the Pacific Ocean or in Sørensen et al., 2012 for the Mediterranean Sea), we suggest that different probabilities can be ascribed to different source zones, according to the expert opinion to be considered.

If we compare the source zones presented here and the ones that have been recently proposed by the SHARE project (2012) for Probabilistic Seismic Hazard Assessment (PSHA) (both shown in Fig. 3), we can see clearly that both were designed for different purposes. While in PTHA it is important to use credible fault scenarios for the generation of tsunamis in each source zone, this consideration is less relevant for PSHA. This implies that source zoning used for PSHA cannot be used for PTHA without a critical review that takes into consideration the known tectonics in the region, as was done in the present work.

Our proposed fault model for the source of large earthquakes and tsunamis comprises a relationship between magnitude, fault-slip and fault dimensions that was inspired on the semi-empirical scaling laws proposed by Manighetti et al. (2007). The law parameters were constrained by the scarce information selected available on large earthquakes in the area. Based on the derived model and the predicted fault slip rates by Cunha et al. (2012), we estimate a minimum recurrence period of circa-3600 and 10 000 yr for events of $M_w = 8$ and $M_w \sim 8.7$ ("1755-like"), respectively, if a single structure (or single combination of structures) is considered. If, however, we take into account the several mapped major active faults in the region, the estimated recurrence periods are reduced to 700 and 3500 yr or less, respectively. Moreover, it is likely that due to the proximity between most of the mapped structures, large earthquakes will happen clustered in time due to fault interaction.

We suggest that the derived earthquake generation model, which departs significantly from the scaling laws proposed by Manighetti et al. (2007), is explained by the structural complexity of the Gulf of Cadiz-SW Iberia region, characterized by moderate, diffuse seismicity, generated at depths attaining 30 to 60 km, in oceanic, transitional and thinned continental-type lithosphere. We believe that the joint use of thin-sheet lithospheric modelling (as in Cunha et al., 2012) together with credible fault models can be applied to estimate the earthquake and tsunami hazard in other complex tectonic environments with long earthquake cycles (larger than 1000 yr).

One of the most uncommon features of the fault model proposed is the lithospheric thickness that we estimate that can be ruptured during a large earthquake (~ 70 km). This thickness exceeds what is expected for a cooling oceanic lithosphere with a Jurassic age, if we take the 600 °C isotherm as a reference for the definition of the lithosphere brittle layer. By computing an estimate of the relative plate velocity based on the known seismic activity, we showed that this fault rupture model is compatible with the current kinematic models for the convergence between Nubia and Eurasia in the Gulf of Cadiz.

Supplementary material related to this article is available online at: http://www.nat-hazards-earth-syst-sci.net/13/1/2013/nhess-13-1-2013-supplement.pdf.

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