The 2004 and 2005 Sumatra Earthquakes: Implications for the Lisbon earthquake

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ABSTRACT

The Sumatra mega-earthquake of 26 December 2004 (M_w=9.3) was the strongest earthquake in the world since the 1964 Alaska earthquake and the fifth strongest since 1900. The earthquake occurred at the interface of the India and Burma plates and triggered a massive tsunami that affected several countries throughout South and Southeast Asia. Three months later, on 28 March 2005, about 200 km south of this event but at a greater depth (28 km), occurred a magnitude 8.7 earthquake. This event was probably triggered by stress variations caused by the December mega-earthquake. In this work we describe the rupture process of both earthquakes, estimated from teleseismic broad-band waveform data provided by IRIS-DMC stations. The rupture direction and velocity were determined from common pulse durations observed in P waveforms using DIRDOP computational code (DIRectivity DOPpler effect). The modified Kikuchi and Kanamori method has been used to determine the slip distribution. For the mega-earthquake two segments of 150 km width (along dip) and 990 km total length with different azimuth were estimated, based on the subduction geometry, aftershock distribution and CMT. Results show that the rupture spread mainly to the North with an average velocity of 2.7 km/s. The focal mechanism shows thrust motion on a plane oriented in a NNW-SSE direction and a horizontal pressure axis in the NNE-SSW direction. The fault slip distribution shows the following pattern: 1) the rupture nucleated at the hypocenter as a circular crack breaking a shallow asperity of about 60 km radius during the first 60 sec; 2) after the initial break to the NNW, the rupture propagated during ~180 s and broke a middle large asperity centred at about 360 km from the epicentre; 3) finally, the rupture propagated further to the north and broke a third asperity centred at ~840 km from the epicentre during at least 110 sec. The maximum slip reaches 14 m in the central asperity and the total seismic moment is Mo=3.0x10^{22} Nm (M_w=8.9), which is less than the value given by the ESMC and USGS (the loss of seismic scalar moment was released in a third segment located to the north). The total source duration and rupture length are estimated to be above 350 sec and 990 km, respectively. For the earthquake of 28 March 2005, a rectangular rupture plane with 400 km length (along the strike direction) and 125 km width (along the dip direction) was obtained from the subduction geometry, aftershock distribution and CMT. Results show that the rupture spread during about 110s in the southwest direction with an average velocity of ~3.3 km/s. Most of the seismic moment was released at the break of two asperities: the largest one located at about 90km from the hypocenter, and the other one at 175 km from the hypocenter. These two asperities correspond on the surface to the areas most affected by the event (Nias Island). The maximum slip reaches 11.5 m in the largest asperity and the total seismic moment is Mo=0.82x10^{22} Nm (M_w=8.6). The focal mechanism shows thrust motion similar to this shown by the mega-earthquake. Probably, the 1755 Lisbon earthquake (M_w~9.0) released as much or more energy as any seismic event of recorded history prior to 2004 December. Nevertheless, the location of the source, responsible for the Lisbon tsunami, is not well known; the epicentres suggested by various authors are separated by some hundreds of km. We compare the similarities and differences of these two mega-earthquakes (Sumatra and Lisbon) with the purpose of reducing the uncertainties relative to the location of the seismogenic zone responsible for the 1755 Lisbon earthquake. Lessons learned from the Sumatra earthquake, through scientific studies, should help to reduce the number of victims and damage during future earthquakes in Portugal.

INTRODUCTION

On December 26, 2004, a great earthquake occurred at 00:58:50.7 (UTC) (6:58 a.m. local time) off the west coast of northern Sumatra, Indonesia (Fig. 1). The magnitude 9.3 of the seismic event, given by the EMSC, located nearly Pulau Simeulue Island (3.50°N, 95.72°E, Fig. 1), classifies it as being one of the five largest earthquakes in the world since 1900 (Mw=9.0, 1952, Kamchatka; Mw=9.1, 1957, Andreanof Islands, Alaska; Mw=9.5, 1960, Chile; Mw=9.2, 1964, Prince William Sound, Alaska) and the largest since the 1964 Alaska earthquake. Three months after the Sumatra mega earthquake, the region was affected again by a great event, on the 28th of March, at 16:09 UTC (Borges et al., 2004). This one has a magnitude Mw= 8.6 with the epicentre located at Lat =2.16, Long =97.17, EMSC, approximately 200km SE of 26th December's (Fig. 1). This hypocenter is deeper (H=28km) than the previous one.

These thrust-faulting earthquakes, occurring at the interface of the India and Burma plates and along the same Sunda Trench fault line, were caused by the release of stresses that develop as the India plate subducts beneath the overriding Burma plates (Fig. 1). The two plates are converging (dextral-oblique convergence) at a rate of 6 cm/yr (Tregoning et al., 1994) and the complex tectonics of the region involves several plates: Australia, Sunda, Eurasia, India and Burma plates (Fitch, 1972; McCaffrey et al., 2000; Bock et al., 2003; Simoes et al., 2004; Bilham et al., 2005).

Due to this elevated convergence rate, the region where both earthquakes occurred is one of the world's most seismically active regions. Earthquakes with a magnitude greater than 7.0 struck the area in 1797, 1833, 1861, 1897 1881 (2 events), 1907, 1935, 1941 and 2000 (Newcomb and McCann, 1987; Ortiz and Bilham, 2003). The consequences of the 26 December in the whole Pacific area were devastating: the earthquake triggered massive tsunamis that affected several countries throughout South and Southeast Asia: Indonesia, Sri Lanka, India, Thailand, Somalia, Myanmar, Malaysia, the Maldives, Tanzani and Bangladesh. The tsunami crossed into the Pacific Ocean and was recorded along the west coast of South and North America. Tsunamis also took place on the coasts of Cocos Island, Kenya, Mauritius, Reunion,

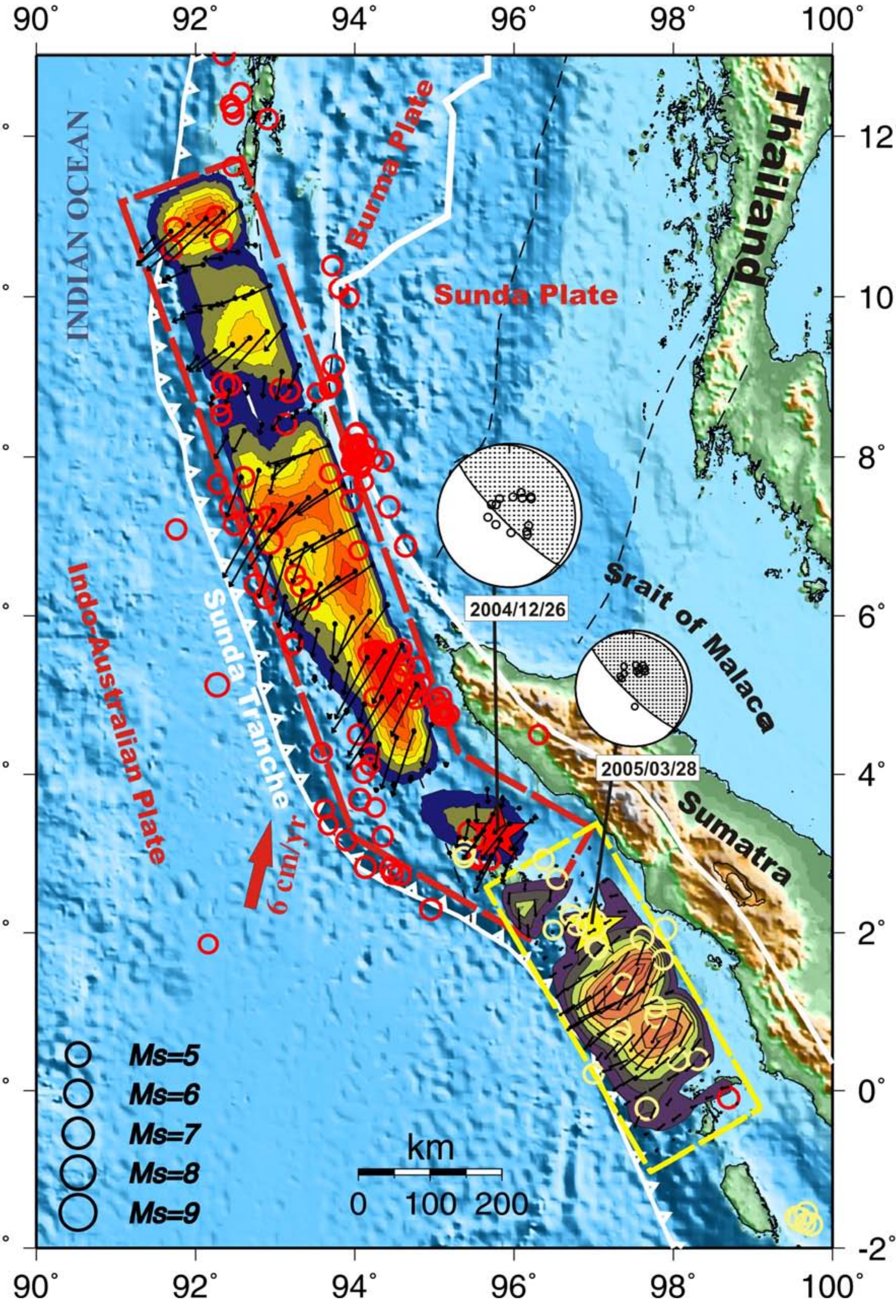

Fig. 1 Map of the region with main tectonic background and some results. Stars indicate epicentres of 26 December 2004 and 28 March 2005 earthquakes; dashed rectangles represent extent of the fault plane of the first and second event; open circle - large aftershocks (M>5.5, epicentres compiled from USGS). The thick arrow indicates direction of the movement between adjacent plates: the India plate moves toward the northeast with a rate of about 6 cm/year relative to the Burma plate. Isolines represent the slip distribution of the first and second ruptures and thin arrows the slip vectors.

and the Seychelles. The earthquake was felt (VIII) at Banda Aceh and (V) at Medan, Sumatra. It was also felt in Bangladesh, India, Malaysia, the Maldives, Myanmar, Singapore, Sri Lanka and Thailand. As a result of the earthquake the sea floor experienced an uplift of several meters. A tsunami survey team from USGS documented wave heights of 20 to 30 m at the island's NW end and found evidence suggesting that wave heights may have ranged from 15 to 30 m along at least a 100 km stretch of the northwest coast.

The spatial distribution of the re-locations of larger aftershocks of magnitude M>5 following the main shock (Fig. 1) suggests a length and width of the rupture of about 1300 km and 200 km, along the the Norten Sunda Trench, respectively.

The March 28, 2005 earthquake was probably triggered by stress variations caused by the December 26, 2004 (Mw=9.3) Sumatra mega-earthquake. The aftershock activity 72 hours after the main shock (36 events with M>5) suggests a length and width of the rupture of about 400 km and 125 km, respectively (Fig. 1). This event generated a moderate tsunami with recorded waves estimated at up to 4-5 meters and with an amplitude of up to 2m near Kirinda in southern Sri Lanka. Smaller waves up to 0.5 meters tall also brushed the coastline in the capital Colombo (W coast of the island). The waves were recorded approximately three hours after the earthquake.

In this work, we have determined the rupture process of the 2004 (Mw=9.3) and 2005 Sumatra (Mw=8.7) earthquakes using teleseismic broad-band data. We compare also the similarities and differences between the Sumatra mega-earthquake with that of Lisbon occurring in 1755. Our purpose is to reduce the uncertainties relative to the location of the seismogenic zone responsible for the 1755 Lisbon earthquake.

DATA PROCESSING

Source process study was performed using 29 and 23 teleseismic P waveforms data recorded at IRIS-DMC stations retrieved via the Internet, for the earthquakes of 26 December 2004 and 28 March 2005, respectively. Stations were selected from the standpoint of good azimuthal coverage and correspond to seismograms recorded at distances ($30^o<D<90^o$) in order to avoid problems with the upper mantle wave triplications, and diffractions of the mantle-core boundary.

DIRECTIVITY

We determine the rupture direction and velocity for both earthquakes from common pulse durations observed in P waveforms using Caldeira (2004) DIRDOP computational code (DIRectivity DOPpler effect

- *The 26 December 2004 earthquake.* Three different time intervals are revealed: 1) between 0-30s we observe a small rupture velocity (vr=0.5±0.5 km/s); the low value obtained for the rupture velocity in this interval suggests a bilateral or circular rupture; 2) between 30-90s a predominant rupture happens mainly towards the NW with a moderate rupture velocity (vr=1.9±0.3 km/s); 3) finally, in the third time interval, between 90-130s, the rupture is mainly to NW with a velocity of (vr=2.7±0.6 km/s).

- *The 28 March 2005 earthquake.* The direction and velocity of the rupture obtained for a time interval between 25-60 sec. show a rupture that spreads clearly to SSW (N153^{o}E) direction with a velocity of (v_r=3.3±0.6 km/s).

INVERSION

The modified Kikuchi and Kanamori (2003) method, based on a finite fault inverse algorithm, was used to carry out the slip distribution. Data were band-passed between 0.002–2 Hz, and converted to ground displacement with a sampling rate of 1Hz.

- *The 26 December 2004 earthquake.* Due to the extreme complexity and large extension of the rupture area of the mega-earthquake we opted to divide the rupture surface into two planes (from South to North) of about 150 km and 840 km with azimuths 305^o and 345^o, respectively. These values were chosen in agreement with aftershock distribution, CMT and orientation of the subduction. For all segments we chose a dip of 10^o and a width of 150 km. We used a 1D 3 layer velocity model with 2.5 km water based on a model proposed by Simoes et al., (2004). For the inversion we selected and analysed 14 teleseismic broad-band data and we inverted a total seismic window of 350 sec length.

- *The 28 March 2005 earthquake.* In agreement with aftershock distribution, CMT and orientation of the subduction, a rectangular section with 400 km length and 125 km width was chosen as the plane of rupture. The length and width of this plane was oriented along strike and dip directions with 150^o and 10^o, respectively. The rupture velocity was fixed on 3.3 km/s according to the DIRDOP result. The velocity model is the same as was used in the previous earthquake. A total of 13 teleseismic broad-band P wave data were selected and analysed. A total seismic window of 150 sec length was inverted. We tested different depths for the hypocenter and the best fit is obtained at 28 km depth.

RESULTS

The 26 December 2004 earthquake. The solution obtained shows thrust motion on a plane striking in a NNW-SSE direction and horizontal pressure axes in a NNE-SSW direction (Fig. 1). Results show that the rupture spreads mainly to the North with an average velocity of 2.7 km/s. The fault slip distribution shows the following scenario (Figs. 1 and 2): 1) in the first stage the rupture nucleated at the hypocenter as a circular crack breaking a shallow asperity of about 60 km radius during the first 60 sec (Mo = 0.28 x 10^{22} Nm, Mw = 8.3); 2) in the second stage, the rupture initiated after the initial break and propagated during ~180 s to the NNW and broke a middle large asperity centred at about 360 km from the epicentre (Mo = 2.0 x 10^{22} Nm, Mw = 8.8); 3) finally, the rupture propagated further to the north and broke a third asperity centred at ~840 km from the epicentre during at least 110 sec (Mo = 1.0 x 10^{22} Nm, Mw = 8.7). The main direction of the displacement occurred along the dip. The maximum slip reaches 14 m in the central segment and the total seismic moment released is Mo = 2.9 x 10^{22} Nm (Mw = 9.0), which is inferior to the value given by the ESMC and USGS. The total source duration and rupture length are estimated to be above 350 sec and 930 km, respectively.

The 28 March, 2005 earthquake. The solution obtained shows dip-slip thrust motion on a plane striking in a NNW-SSE direction and horizontal pressure axes in NNE-SSW direction (Fig. 1). The moment-rate function (Fig. 2) shows mainly two peaks: the first, and the largest one, is centred about 55 s and the second maximum is centred about 60 s. The rupture spreads mainly to the South with a slip average vector normal for the strike rupture (Fig. 1). The spatio-temporal fault slip distribution (Fig. 2 shows the following scenario: in the first stage the rupture nucleated at the hypocenter during the first 15 s as a circular crack; after that, the rupture propagated mostly unilaterally to the SSE direction along 300km, breaking mainly two asperities. The largest one is centred about 90 km and the other one at 175 km from the epicentre. The maximum slip reaches 11.5 m in the largest asperity and the total scalar seismic moment released is Mo = 0.82 x 10^{22} Nm (Mw = 8.6), which is in agreement with values given by the EMSC and USGS. The total source duration and rupture length are estimated to be nearly 110 sec and 425 km, respectively.

DISCUSSION

For the 26 December, 2004 earthquake the constrained dimension of the fault is nearly 930 km with a maximum rupture velocity of 2.7 km/sec during 350 sec. The rupture process can be explained by 3 asperities distributed between a depth of approximately 5 km and 20 km with a time duration of 350 sec. The total scalar seismic moment is 2.9x10^{22} Nm

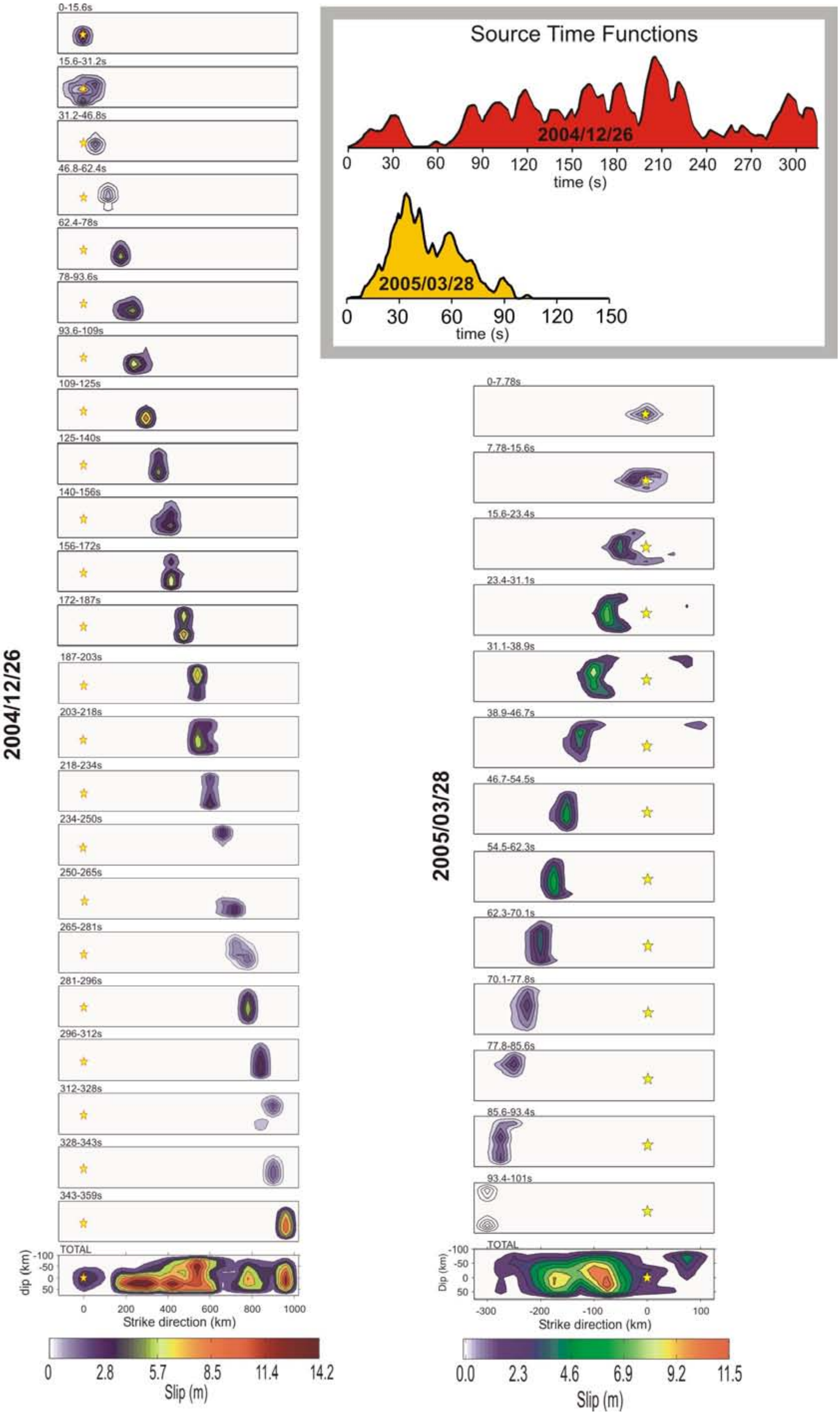

Fig. 2. Spatio temporal evolution of the ruptures obtained at equal time intervals for ours preferred models. See text for details.

(Mw=9.0) and the maximum slip is about 14 m at the second segment (Fig. 1), where most of the seismic energy that was released occurred (second and third).

However the rupture process presented in this study is incomplete; we can solve only about three quarters of the total scalar seismic moment determined by the EMSC and USGS. We believe that the divergence between our result and the results of official agencies is the seismic scalar moment released in the third segment located at the north, whose existence is suggested by aftershock distribution. The source process is too long to analyse the total rupture with this program. We need to adapt the program in order to analyse the total seismic rupture process. It is important to refer to the fact that we have not introduced PP and PPP phases, which can influence the inversion result (Kanamori and Alemberger, 2005).

The Analysis of the normal modes according to Jeffrey et al. (2005) and Stein and Okal (2005) give Mo = 6.5 x 10^{22} Nm (Mw=9.2) and Mo = 1.3 x 10^{23} Nm (Mw = 9.3) respectively. Compared with these results, our results explain only 44% of the total seismic moment. The inversion with the body wave could retrieve only the “short period” image of the source process (T<300 s). The main radiated energy is above 300s; however, for these frequencies it is not possible to retrieve details of the rupture process.

For the 28 March 2005 earthquake the constrained dimension of the fault reaches almost 425 x 125 km and the rupture velocity was fixed at 3.3 km/sec, according to the result obtained by the directivity analysis. The rupture spreads mainly to the South during 110 sec. The source process is characterized by unilateral rupture propagation and the slip average vector is nearly normal for the strike of the fault (dip-slip thrust motion), as expected from the relative motion between the two plates involved. The total moment released can be explained by 2 asperities, centred at 90 and 175 km SSE from the epicentre, where most of the seismic energy was released. Geographically

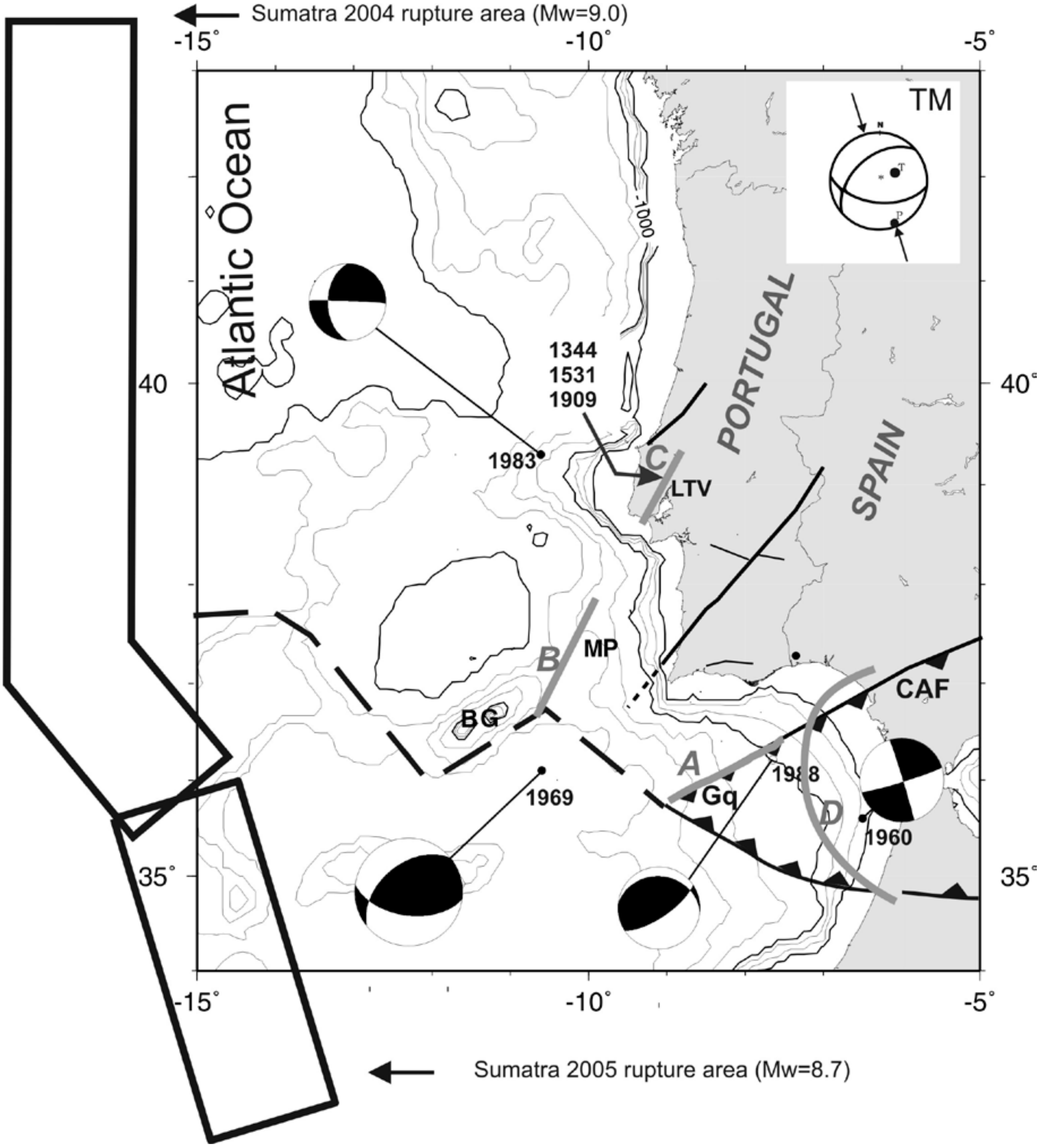

Fig. 3 Comparison between the 2004 and 2005 Sumatra rupture area (rectangles at left) and proposed source of the 1755 Lisbon earthquake (A-B Source model proposed by Baptista et al. 2003; B-C, model proposed by Vilanova et al. (2003); D – model proposed by Gutscher (2004)). Fault plain solution of the main instrumental events of the region. TM represents moment seismic tensor and orientation of maximum compressional regional stress. The square symbols represent the epicentres of the more important historical earthquakes of the area (Borges, 2001). See text for details.

these two asperities correspond to the most affected area (Nias island; Imax = IX according USGS report). The total scalar seismic moment is 0.82 x 10^{22} Nm (Mw = 8.6), whereas the maximum slip is about 11.5 m (Fig. 2). The maximum slip is concentred in a small area between 20 and 35 km deep, which can justify the small tsunami generated by the earthquake.

The slip distribution determined in this study corroborates the unilateral character of the rupture process of both Sumatra earthquakes, with a predominant rupture towards the NNW and SSE, for the 26 December, 2004 and 28 March, 2005 earthquakes, respectively.

IMPLICATIONS FOR THE LISBON EARTHQUAKE

Observations from the mega earthquake of December 2004 in Sumatra offer new insights concerning rupture and tsunami generation in great subduction earthquakes, which may be applicable to the study of the 1755 earthquake and tsunami. The earthquake of 1755 generated a tsunami that produced waves about 6 m high at Lisbon, 15 m high along the coast of the Algarve, and 20 m high at Cadiz, Spain. The waves traveled on to Martinique, a distance of 6100 km in 10 hours, and there rose to a height of 4m. For the Sumatra mega-earthquake the waves may have been 15 to 30 m high along the entire 100 km stretch of coast from Kreung Sabe to the northwest of the island (USGS).

Probably, the great Lisbon earthquake of 1 November 1755 (M_w~9.0) released as much or more energy as any seismic event of recorded history prior to December, 2004. The Azores-Gilbratar fracture zone (AGFZ) marks the boundary of active tectonic interaction between the African and the Eurasian plates. This is an active seismic region where large earthquakes occur with frequency and some of them, near the eastern segment of AGFZ, are capable of generating tsunamis. The tectonic interaction on the eastern segment of AGFZ involves a thrusting component in a NW direction along a NE-trending strike plane (Buforn et al., submitted). The epicentre of the Lisbon earthquake reported in the literature is (38.0°N, 9.0°W) in the Atlantic Ocean, about 200 km WSW of Cape St. Vincent (Fig. 3). However, this estimate appears to be incorrect. It is believed that the epicentre was further south and west than has been postulated, since the first of the tsunami waves reached Lisbon about 40 minutes after the quake struck. Nevertheless, the location of the source responsible for the Lisbon tsunami is not well known; the epicentres suggested by various authors are separated by some hundreds of km. Some studies have suggested fault rupture closer to the coast of Portugal, while others have proposed a complex source involving both a larger earthquake on the AGFZ and a second, triggered fault rupture closer to Lisbon (Vilanova et al., 2003). Furthermore, the first tsunami waves were observed in the Tagus estuary immediately after the end of the seismic shaking, rather than 45 to 90 mn after the end of the quake, as was the case on the Atlantic coast to the North and the South. This point involves a second fault rupture on an active fault in the Lower Tagus Valley or else a submarine landslide within the Tagus estuary. Baptista et al. (2003) proposed a composite source of the 1755 earthquake, including the Marquês de Pombal thrust fault and the Guadalquivir Bank.

Recently, based on cruise data (heat flow, bathymetry, active mud volcanoes, and seismic profiles) Gutscher (2004) proposed that the Lisbon earthquake may have nucleated along a small subduction zone beneath the Gulf of Cadiz and the Straits of Gibraltar.

There is great variety in the manner in which an earthquake rupture spreads across a fault. However the fundamental characteristic of the propagation of an earthquake rupture is based mainly on the rupture directivity: unilateral or bilateral? Based on a study of large and moderate shallow earthquakes (Mw≥7.0) McGuire et al. (2002) show that the majority of large earthquakes have a predominantly unilateral rupture. This observation quantifies what appears to be a general property of large earthquake dynamics. The unilateral character determined in this study, for both Sumatra earthquakes (Mw=9.3 and Mw=8.7), supports the observation made by McGuire et al. (2002) that the ruptures are predominantly unilateral, while all the models for the mega 1755 source (M_w~9.0) presented previously are based on a complex or a bilateral rupture. These models are contrary to the majority of large earthquakes indicating dominantly unilateral rupture. Furthermore, numerous studies of extended-source earthquake models of spatial and temporal evolution of earthquake slip on fault planes show that the slip is spatially variable and 48% of the events nucleate in regions of low slip (Mai et al. 2005). This behaviour is also observed in the Sumatra 2004 and 2005 earthquakes (Figs. 1 and 2). Then the uniform slip models proposed for the source of the 1755 earthquake must be reviewed in order to incorporate these characteristics (unilateral rupture and heterogeneity of slip distribution) and probably most extended ruptures must be considered.

The slip distribution of the Sumatra earthquake of 2004, determined in this study, suggests that the magnitude 9.3 ruptured a fault patch roughly the size of the entire Portugal Atlantic margin Zone (Fig. 3). This comparison, between the 1755 and Sumatra earthquakes, is probably excessive; nevertheless their impact and the socioeconomical loss are comparable. The source of the 1755 earthquake must also be investigated in a more general geodynamic related context, for instance, to active incipient subduction zone located on the west Iberian margin as suggested by Ribeiro (2002).

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REFERENCES

Baptista M. A., J. M. Miranda, F. Chierici, and N. Zitellini, 2003. New Study of the 1755 Earthquake Source Based on Multi-channel Seismic Survey Data and Tsunami Modeling. Natural Hazards and Earth System Sciences, 3: 333–340.

Borges J.F., B. Caldeira and M. Bezzeghoud, 2004. Source Rupture Process of the Great Sumatra, Indonesia Earthquake (Mw=8.9) of 26 December 2004. Preliminary Results. http://www.cge.uevora.pt/get_file.php?id=274

Buforn E., M. Bezzeghoud, A. Udias and C. Pro, 2004. Seismic source in the Iberian-African plate boundary and their tectonic implications. Pageoph, 161, 3, 623 – 646

Bilham, R. , E. R. Engdahl, N. Feldl and S. P. Satyabala, 2005. Partial and Complete Rupture of the Indo-Andaman plate boundary 1847-2004, submitted to Seism. Ress. Lett.

Bock, Y., L. Prawirodirdjo, J.F. Genrich, C.W. Stevens, R. McCaffrey, C. Subarya, S.S.O. Puntodewo, and E. Calais, 2003. Crustal motion in Indonesia from Global Positioning System measurements, J. Geophys. Res., 108, 2367, doi:10.1029/2001JB000324.

Borges, J. F., Augusto J.S. Fitas, M. Bezzeghoud and P. Teves-Costa, 2001. Seismotectonics of Portugal and its adjacent Atlantic area. Tectonophysics, 337, 373-387.

Caldeira B., 2005. Caracterização espaço-temporal da fonte sísmica. Processo de ruptura e directividade. PhD thesis, University of Évora, Évora, Portugal, 282 p.

Fitch, T.J., 1972. Plate convergence , transcurrent faults and internal deformation adjacent to SE Asia and western Pacific. J. Geophys. Res., 77,4432-4460.

Gutscher, M.-A., 2004. What caused the Great Lisbon Earthquake? Science, 305, p. 1247-1248.

Park, J., T. R. Song, J. Tromp, E. Okal, S. Stein, G. Roult, E. Clevede, G. Laske, H. Kanamori, P. Davis, J. Berger, C. Braitenberg, M. Van Camp, X. Lei, H. Sun, H. Xu, and S. Rosat, 2005. Earth's Free Oscillations Excited by the 26 December 2004 Sumatra-Andaman Earthquake, Science, 308, 1139-1144.

Ribeiro A., 2002. Soft Plate and Impact Tectonics. Springer Ed., 324 p.

Kanamori H., and D. Helmberger, 2005. Energy radiation from the Sumatra earthquake, Nature, 434, 582.

Kikuchi, M. and H. Kanamori, 2003. Note on Teleseismic Body-Wave Inversion Program, http://www.eri.u-tokyo.ac.jp/

McGuire, J. J., L. Zhao, and T. H. Jordan, 2002. Predominance of unilateral rupture for a global catalog of earthquakes, Bull. Seismol. Soc. Am. , 92 , 3309-3317.

Newcomb, K. and McCann, W., 1987. Seismic history and seismotectonics of the Sunda arc, Jour. Geophys. Res., 92, 421-439.

Ortiz, M., and R. Bilham, 2003. Source area and rupture parameters of the 31 December 1881 Mw = 7.9 Car Nicobar earthquake estimated from tsunamis recorded in the Bay of Bengal, J. Geophys. Res., 108(B4), 2215, doi:10.1029/2002JB001941.

Simoes, M., J. P. Avouac, R. Cattin, and P. Henry, 2004. The Sumatra subduction zone: A case for a locked fault zone extending into the mantle, J. Geophys. Res., 109, B10402, doi: 10.1029/2003JB002958.

Stein, S. and E.A. Okal, 2005. Sumatra earthquake: Gigantic and slow, Nature 484,581-582.

Tregoning, P., F. K. Brunner, Y. Bock, S. S. O. Puntodewo, R. McCaffrey, J. F. Genrich, E. Calais, J. Rais, and C. Subarya, 1994. First geodetic measurement of convergence across the Java Trench, Geophys. Res. Lett. 21, 2135–2138.

Vilanova S. P., C. F. Nunes and J. F. B. D. Fonseca, 2003. Lisbon 1755: A Case of Triggered Onshore Rupture? Bull. Seismol. Soc. Am; 93; no. 5; p. 2056-20