THE GEODYNAMIC MEANING OF THE GREAT SUMATRAN EARTHQUAKE: INFERENCES FROM SHORT TIME WINDOWS

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Abstract: *The difference between the value of seismic moment computed using the surface wave data and the value derived from the normal modes of the Earth requires reinterpretation of the focal mechanism of the Great Sumatran Earthquake (TU=26 December 2004 - 00h 58m, Lat=3.3°N, Lon=95.8°E, H=30 km, M=9.3) based on the second conjugate – near vertical CMT fault plane solution. The displacement of the Earth's instantaneous rotation pole – observed at ASI of Matera, Italy –, the seismic data (USGS) in the two days following the main shock, the high frequency P-wave radiation, the geomorphologic data, and the satellite data of uplift/subsidence of the coasts (IGG) converge toward this interpretation. A thorough revision or a complete overcoming of the subduction concept is then needed.*

Introduction

A great earthquake shocked the Sumatra region on December 26, 2004 (Lat=3.3°N, Lon=95.8°E, H=10 km, TU=26 December 2004- 00h 58m, M_w=9.3). The event was accompanied by a disastrous tsunami that killed 280,000 people. The extreme magnitude has placed the shock as one of the greatest events in the last hundred years. Some difficulties have arisen in interpretation of this event because the alleged geometry of the convergence of the Indian plate is in some segment of the Sunda Arc practically parallel to the arc. Other difficulties came from the discrepancy between the Mw (estimated from surface wave T>40s) and the magnitude M derived from the normal modes of the Earth. Moreover some tried to model the fault plane as a subhorizontal rectangle of approximately 200 × 400 km which are at odds with the behaviour of the phenomena in the first hours and days after the main shock.

Because subhorizontal faulting is so unrealistic, I will try to give a new interpretation of the Sumatran earthquake which is contradictory with the subductive solutions. While this work was being prepared, many other clues in favour of the alternative interpretation arrived from published reports, allowing this paper to become a short review.

The shift of the Earth's instantaneous rotation pole

A displacement of near 1.5 mas (milliarcsecond; 1.0 mas ≈ 3.0 cm) of the instantaneous rotation axis of the Earth has happened nearly coseismically during the Sumatran earthquake. The displacement of the centre of mass of the Earth was instead undetected and was probably very small and under the threshold of instrumental detectability. The displacement has been observed by Giuseppe Bianco at the ASI (Italian Space Agency) of Matera SLR Observatory, but still no interpretation of this data has been provided. It is the first time that this kind of displacement is observed with certainty thanks to new high-precision astrogeodetic technologies.

The observed instantaneous Earth rotation pole has passed abruptly from a larger polhody 'orbit' to a more inner one (Fig. 1a & b), and the two nearly concentric orbits are separated by a distance of ≈ 1.5 mas (Fig. 1b). This distance has been evaluated on a line perpendicular to both old and new orbit. But this cannot be considered the true displacement of the instantaneous rotational pole. An extrapolation to the future should be made to know the expected position of the rotational pole of December 26. Three vector of the rotational pole displacement each in a two-day interval have been used to evaluate a vectorial average of the expected two-days displacement (see the dotted empty red circle in Fig. 1b). The distance between the expected 26 December pole and the observed one is now of nearly 3.0 mas (nearly 9.5 cm), and the azimuth of displacement appears to be exactly opposite to the epicentral azimuth (Longitude ≈ 96°).

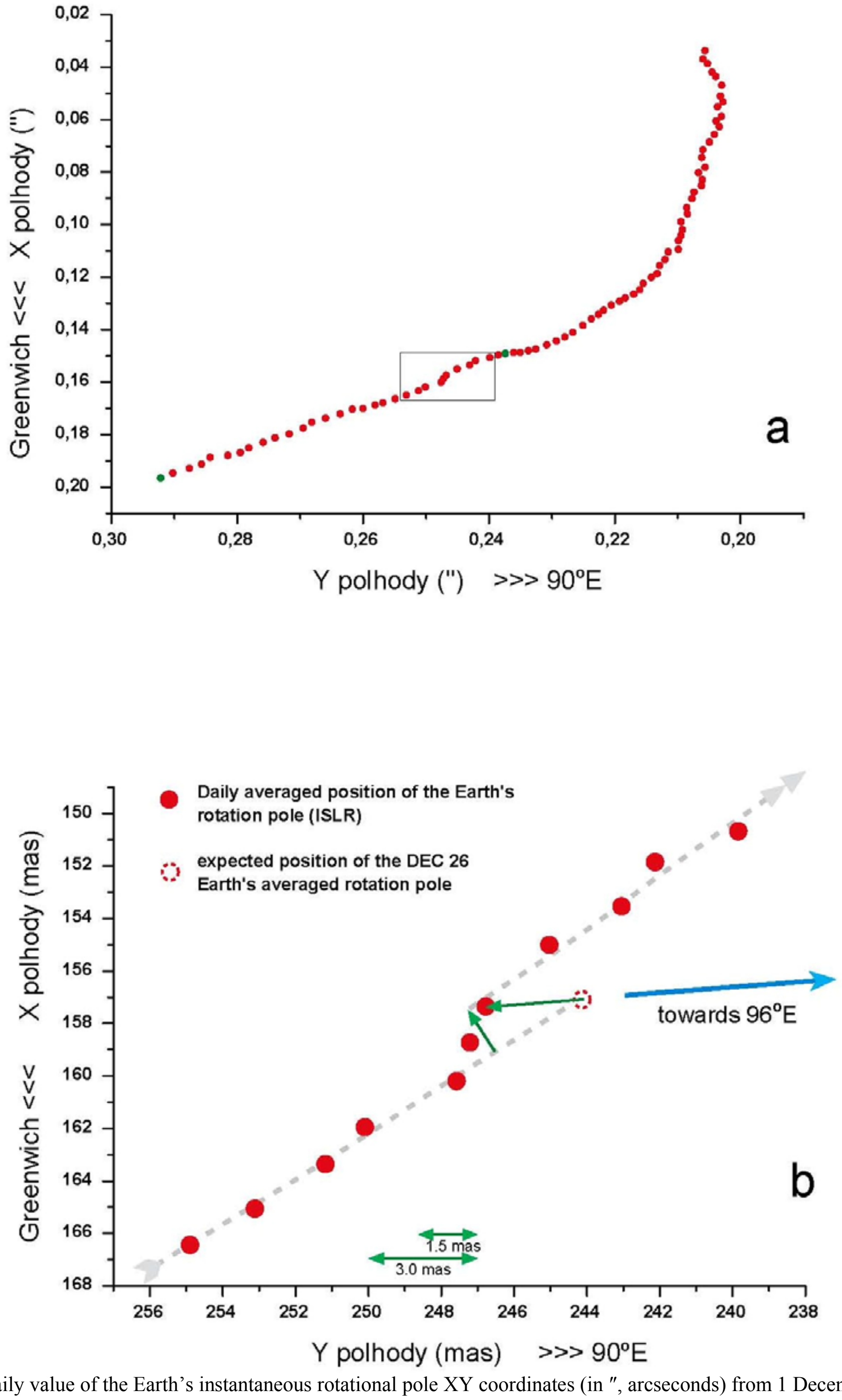

Fig. 1. a) Daily value of the Earth's instantaneous rotational pole XY coordinates (in ″, arcseconds) from 1 December, 2004 to 22 February, 2005 (ISLR data from IERS). The small box encloses the data from 21 to 30 December, 2004.

b) Zoom on the time window 21-30 Dec. While the distance between the 'orbits' of the polhody before and after the great Sumatra earthquake is near 1.5 mas – without directional relation to the epicentral position –, the difference between the expected and the real position of the daily averaged value of the instantaneous rotation pole is 3.0 mas. It is noticeable that the vector from the expected position to the measured position is exactly opposite to the epicentre position.

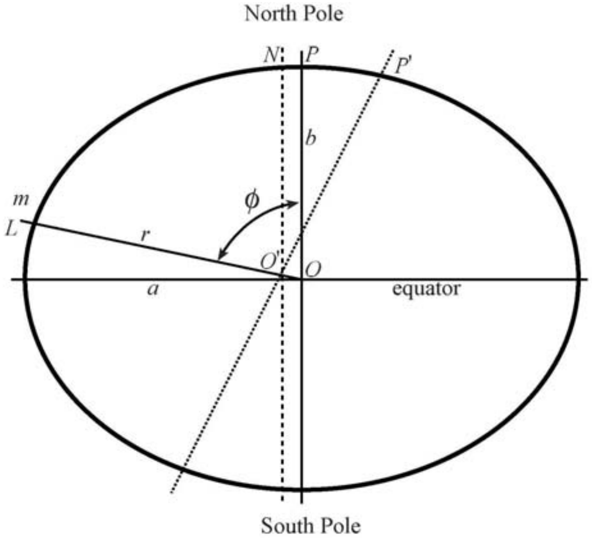

Fig. 2. If a mass *m* is inserted in a point of latitude L (colatitude ϕ), a displacement of the geocenter from O to O' happens, with a displacement of the principal axis of inertia from P to P'. The contribution of NP to the total polar motion is opposite in the two hemispheres. The scale of the equatorial radius *a* is enhanced with respect to the polar radius *b*.

I tried to get general information on the geodynamics of the Earth following a line of reasoning already developed in preceding papers (Scalera, 1999, 2002 & 2003). The simple procedure can be considered a sort of inversion of the polar motion data toward information about the mass movement at the earthquake source (Scalera, 2005b).

In the case a neat protrusion, or extrusion, of mass has happened during the earthquake with the epicentre located near 3.5 geographical degrees north of the equator, the inertial axis of the planet must be displaced toward the area far from the extrusion zone. Immediately the instantaneous rotational pole has to recover its position toward the same direction. Because the rotation axis does not move with respect to the celestial reference frame, it is better to say that the whole Earth's body rotates until the new inertia axis comes again in exact coincidence with the mean rotational pole. The opposite displacements must occur if an intrusion, or subduction, of mass occurs north of the equator. Then the observed impulsive axial movement – if confirmed and if my interpretation is right – gives support for the hypothesis of a prevailing upward movement of mass near the Wadati-Benioff zone.

In the case of a rigid Earth (Schiaparelli, 1883 & 1891), it is possible to prove, referring to Fig.2 and neglecting higher order smaller terms, that when a mass m is added to the Earth mass M_E at a point L of the surface at a colatitude ϕ in the northern hemisphere (with $m \ll M_E$):

$$(1) \qquad PP' \cong \frac{br^2 m}{2(B-A)}\sin(2\phi) - r\frac{m}{M_E}\sin\phi ,$$

with A and B the equatorial and the polar moment of inertia, respectively.

In (1) the term

$$NP = -r\frac{m}{M_E}\sin\phi$$

arises from the displacement of the centre of mass from O to O' and is normally neglected (Schiaparelli, 1891) because it is considered small in comparison with the first term if the mass transport on the Earth happens with a roughly casual spatial distribution and with a probability nearly equal zero to happen very near the equator. Then, the relation to compute the inertial pole displacement in the rigid case is:

$$PP' \approx W \cdot r\frac{m}{M_E}\sin(2\phi); \qquad \text{with}$$

$$W = \frac{M_E br}{2(B-A)} \cong 460$$

With a simple aim to check the validity of the magnitude orders, let me assume that a rectangular prism base 1000 × 50 km ($50 \cdot 10^9$ m^2) and height 30 km – but the height can also remain undefined – can be representative of the volume displaced during the main earthquake of December 26, 2004.

A vertical displacement of this volume of 10 m is assumed and a mean density of 2.7 g/cm^3 is assigned to the material contained in the volume. The extruded volume is then 10 m × $50 \cdot 10^9$ m^2 = $500 \cdot 10^9$ m^3 and its mass is $2.7 \cdot 10^6$g/m^3 × $500 \cdot 10^9$ m^3 = $13.5 \cdot 10^{17}$ g, which is to say $2.2 \cdot 10^{-10}$ M_E. Considering the presence of the strata of oceanic water (density ≈ 1.0 g/cm^3) covering nearly the totality of the interested region, and its adaptability to quickly recover its undisturbed shape, the contrast of density of the extruded volume is reduced to only 1.7 g/cm^3 and the efficient mass to $8.5 \cdot 10^{17}$ g.

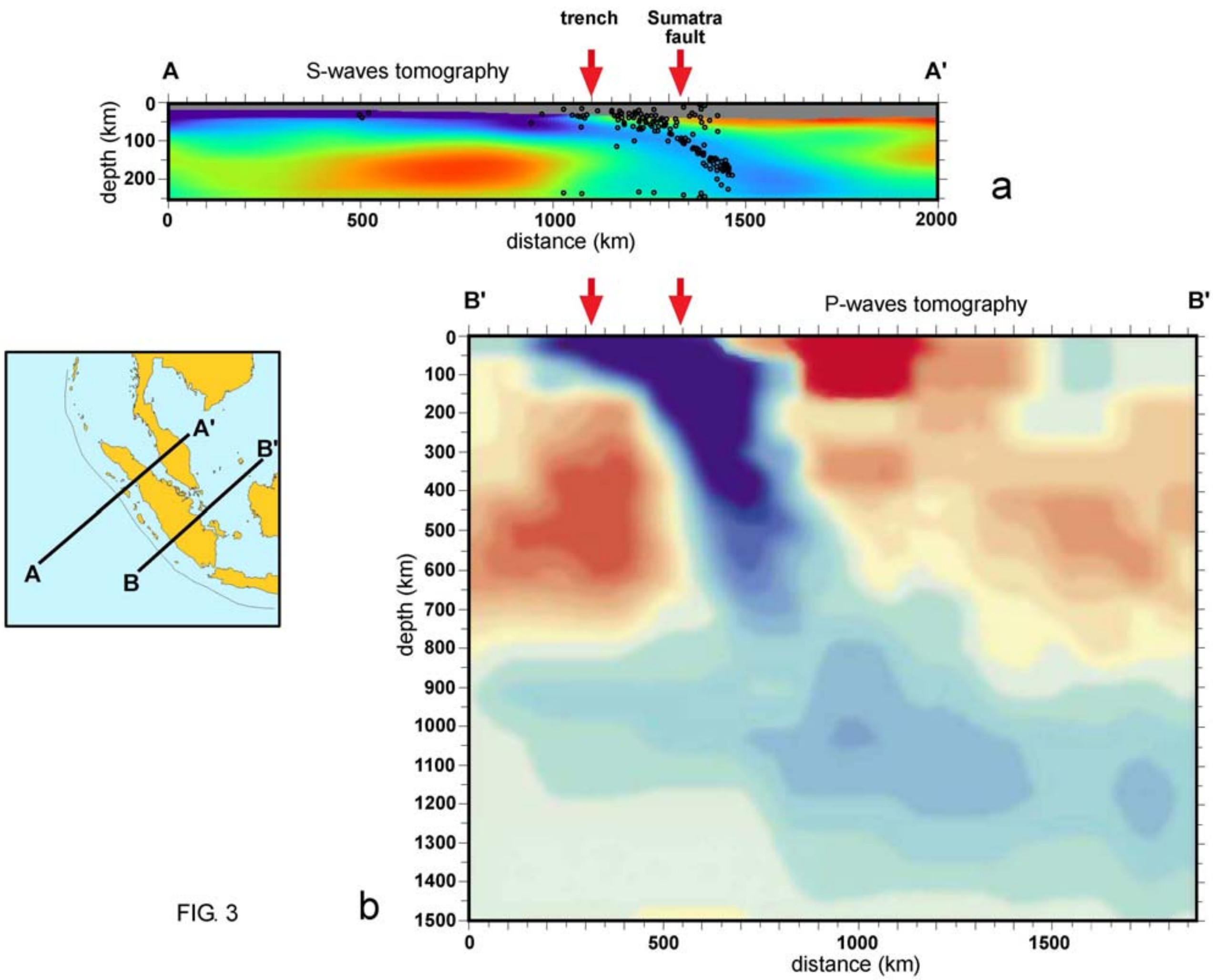

FIG. 3

Fig. 3. Seismic tomographies under the Sunda Arc, retraced at the same horizontal and vertical scale.

a) S-wave tomography by Ritzwoller, Shapiro and Engdahl (2005) along the line A-A’ (see insert for location of the profile) has been redrawn. The resolving power has produced a tomographic image up to the depth of 250 km. The earthquakes of the Wadati-Benioff zone also do not exceed 250 km in depth. A wedgeshaped high velocity zone (blue zone) extending deeper than 100 km is revealed.

b) P-wave tomography by Hafkenscheid, Buitler, Wortel, Spakman and Bijwaard (2001) along the section B-B’ (see insert) has been redrawn. This technique allows a deeper testing of the mantle elastic properties. The wedge of anomalous high velocity mantle can be traced up to a depth of more than 1,000 km. The wedge appears more defined and more vertical in the P-tomography. In this paper an idea is proposed – on the basis of several lines of evidence – that the Great Sumatran Earthquake was caused by upward movement of this mantle wedge. The rising of dunite – a dense mantle material – under the trench-arc zones was an idea of Ott C. Hilgenberg (1933 & 1976), completely unappreciated during his life (Scalera, 2003).

Finally, because a protrusion of the mantle of comparable amount (10 m) should be expected under the crust, a contrast of density should be emplaced over the old Moho discontinuity. A possible reasonable value can be a contrast of ≈ 0.6 g/cm^3 (adopting an undercrustal mantle density of ≈ 3.3 g/cm^3) over all the 10 m uplifted under-Moho material. The further efficient mass to be accounted for is then $0.6{\cdot}10^6$g/m^3 × $500{\cdot}10^9$ m^3 = $3.0{\cdot}10^{17}$ g.

Making the further simplification to apply all the total efficient mass, $11.5{\cdot}10^{17}$ g (that is $1.93{\cdot}10^{-10}\ M_E$) to the epicentral location – namely neglecting the span of nearly five geographical degrees in the parallelepiped base size – the displacement of the inertial axis caused by the extrusion at the water-crust boundary is:

$PP' = 460 \times 6378{\cdot}10^5\text{cm} \times 1.93{\cdot}10^{-10} \times \sin(173°) =$ 6.9 cm ,

while the term related to the displacement of the centre of mass NP is:

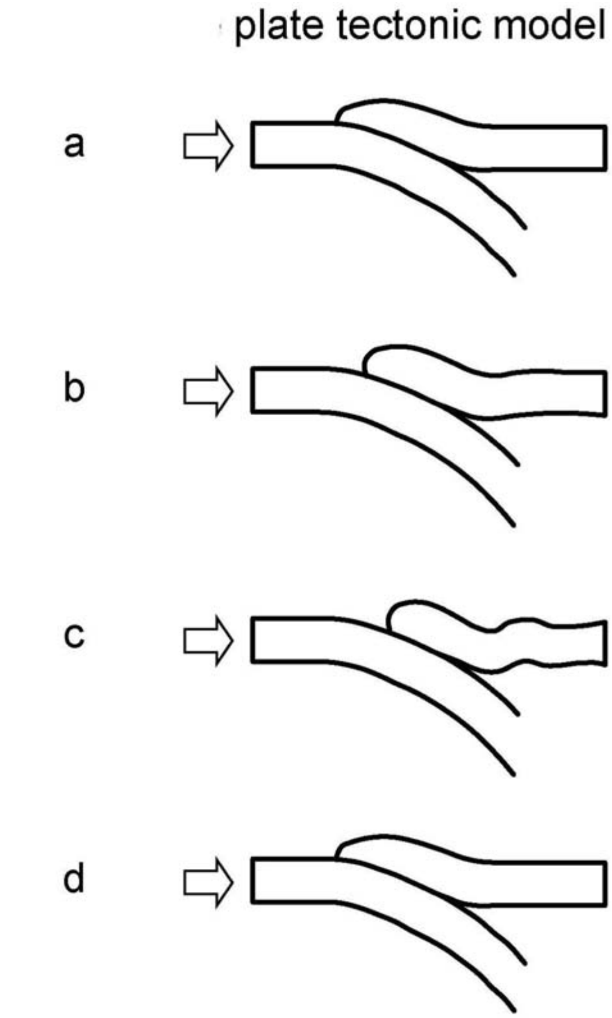

Fig. 4. The plate tectonic model for the occurrence of the shallow earthquakes caused by subduction. The mechanism of accumulation and release of potential energy is considered to be purely elastic in a brittle environment, and is called the elastic rebound model. Because the Sumatran earthquake was a shallow event, this model can be adopted. a) Plunging lithosphere moves – at a rate of few centimetres per year – from the surface toward the transition zone and further on. b) Friction and asperities stick the backarc lithosphere to the plunging oceanic lithosphere allowing them to travel fastened together. c) Fracture starts in the Wadati-Benioff zone allowing the backarc lithosphere to rebound elastically toward the surface, and the subducting lithosphere – free from braking – to suddenly accelerate. d) Two lithospheric slabs have completed their rebound and are ready for a new cycle.

It should be noted that the commonly accepted fault plane solution of the Sumatran earthquake assumes a nearly horizontal slip surface; its horizontality making the above drawn model very difficult to work.

$NP' = 6378 \cdot 10^5 \text{cm} \times 1.93 \cdot 10^{-10} \times \sin(87°) =$ 0.1 cm.

This last value is the displacement of the geocentre from the old position but no

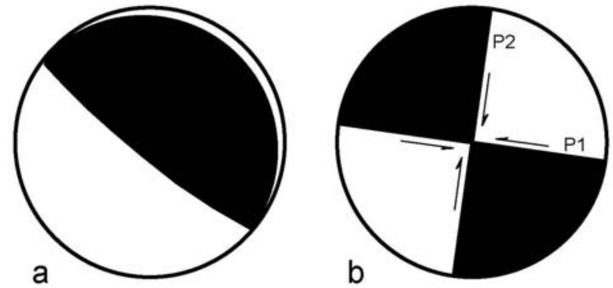

Fig. 5. Focal mechanism. a) Centroid moment tensor (CMT) solution of Harvard is reproduced. Indeed, the CMT provides two possible fault plane solutions for the Sumatran earthquake: P1: (Strike = 329; Dip = 8; Slip = 110) and P2: (Strike = 129; Dip = 83; Slip = 87). The solution P1 is commonly adopted because of compatibility with the plate tectonic model. b) Section of the focal sphere on a vertical plane perpendicular to the strike direction, and the two conjugate fault plane labelled P1 and P2. The P1's very low dip angle of 8° has led to the assumption of sub-horizontal slip. However, many clues are in favour of the near vertical fault solution P2.

displacement of the geocentre occurs on the Earth's orbit, making the detection of its shift with respect to the artificial satellites or to Moon's position very difficult or impossible. Then these values are in agreement with the observation of polar motion shift and the lack of observation of geocentre shift respectively.

If the viscoelastic behaviour of the Earth is taken into account (Lambeck, 1980 & 1988; Spada, 1992 &1997) the introduction of the Love numbers *k* leads to:

$$PP' \approx \frac{br^2 \cdot m(1+k')}{2(B-A)} \cdot \sin(2\phi) \qquad (2)$$

The factor $(1+k')$ assumes values smaller than 1 with k' ranging nearly linearly from a surface value $k'=-0.30$ to an upper-lower mantle boundary value $k'=-0.45$. Then the viscoelastic formula (2) leads to numerical values for PP' few tens percent smaller than the values in the rigid case:

$$PP' \approx 4.1\, cm$$

The values in the rigid case and in the viscoelastic case, although in the right magnitude order, are still too little with respect to the observed data (9.5 cm). This can mean that a more complete account should be provided for the contrasts of density on a larger amount of strata and in the mantle (but with very low

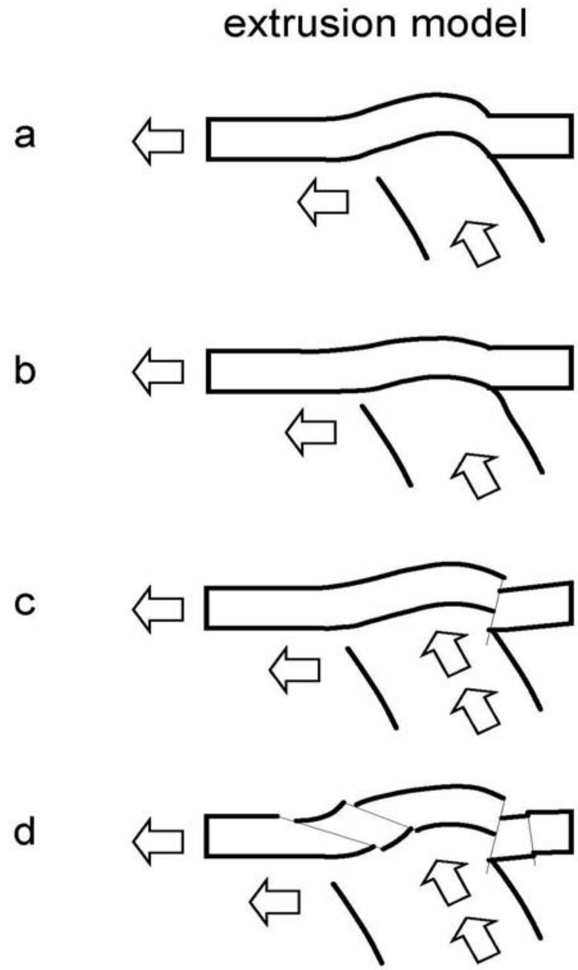

Fig. 6. Alternative model of the shallow arc-zone earthquake occurrence.

a) Initially a process of decoupling of oceanic and continental lithosphere slowly occurs under the arc.

b) The effect of this tensional regime is the subsidence of the bumping arc as witnessed by the coral reef subsidence.

c) Near vertical fracture is eventually produced by a sudden uplift of undercrustal or underlithospheric material pushed upward by a sudden phase change triggered by the tensional regime. The lifted side can have possibly a downward rebound, producing a tilting of the neighbouring plate. This can be in agreement with the observed uplift of the coralline barrier to the west and the subsidence of the larger islands.

d) Finally a plethora of settling new faulting, producing a high number of aftershocks, should be expected diffusely along the entire major fault in a wide area. Lateral spreading of the arc can also be triggered by the main fracture. This spreading can produce subhorizontal fault mechanisms.

density contrast). Moreover a less rough model with a ramp instead of a rectangular prism would contribute for ½ of the required displacement and consequently would require for a greater effect of the density contrasts distributed radially in the crust and mantle or for a greater – twice or more – area of basis (e.g. width 100 km or more). At this stage this approximation is sufficient to prove the correctness of the hypotheses.

If the same amount of mass is hypothesised to be displaced nearly horizontally (≈8°), the effect on the rotation axis would be one order of magnitude smaller.

More generally, the integrated effect of all the earthquakes has been found (Spada, 1992 & 1997) – on the basis of under-thrust character of most earthquakes assumed by Dahlem (1971 & 1973) – to nudge the secular polar motion toward an azimuthal direction nearly opposite to the secular observed one. Then a possible role of earthquakes in driving the secular polar motion was excluded. Nevertheless, on the basis of the effect of the Sumatran earthquake on the rotational pole (Fig. 1ab, Fig. 2), the possibility of extrusion of material instead of subduction should be sought.

In the case of a prevailing extrusion of material (horizontal strike effects should cancel in average) – instead of under-thrust – the integrated effect of the global seismicity would be in the opposite direction from that found by Spada (1997). This time the integrated effect would be in the right azimuthal direction to be a legitimate component (among other causes; e.g. an asymmetrical expansion of the planet can be the main cause. See Scalera, 2002 & 2003) of the polar motion and Chandler Wobble excitation. My personal opinion is that besides the statement that earthquakes make the Earth more round, it should be added that earthquakes make the Earth larger.

Clues from seismic tomography

The S-wave seismic tomography (Fig. 3a) of the Indonesian and Sumatra region reveals – in a series of deep sections – a clear high velocity body that, starting from under the trench, immerges at more or less the classic inclination angle of near 45° up to 200 km depth under the Sunda shelf (Ritzwoller et al., 2005). The epicentre location becomes narrower under the crust and finally the 45° narrow pattern is approached. No earthquakes deeper than 250 km are detected in the seismic history of the arc. More detailed global and regional tomographies

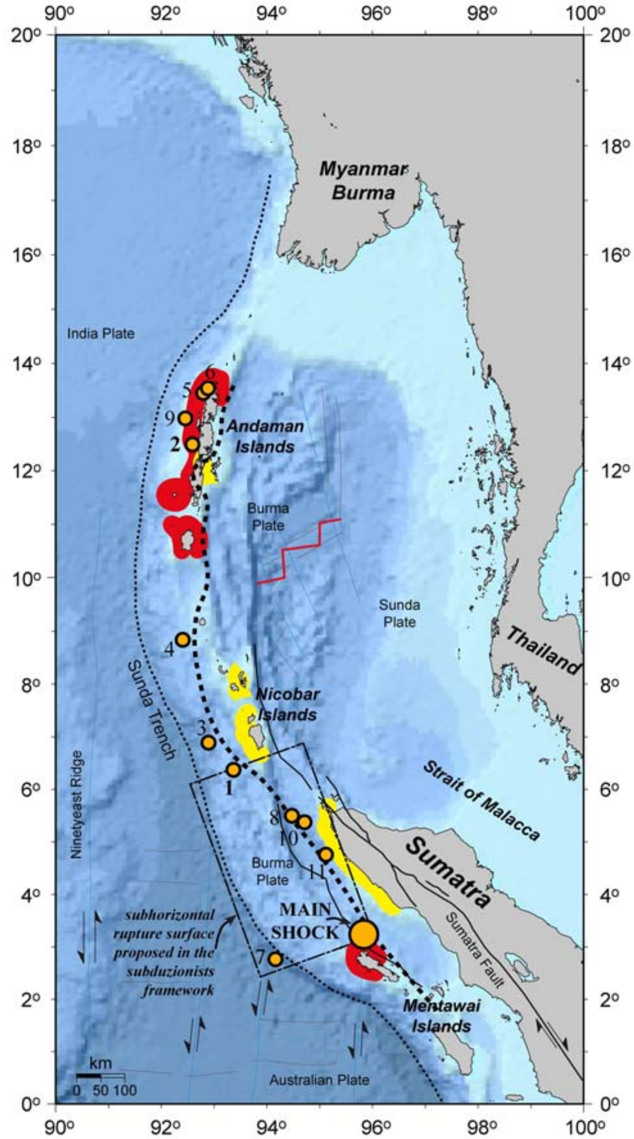

Fig. 7. Major structures of the Sunda arc and epicentres of the Great Sumatran Earthquake within two days following the main shock. Faults and directions of slip are from Sieh and Natawidjaja (2000). Epicentres are from USGS preliminary determinations of December 2004. The emergence and submergence satellite data are from Geographic Survey Institute of Japan (red – uplift; yellow – subsidence). The rectangle of the subhorizontal rupture surface has been traced taking several versions into account, slightly different from that published on the USGS website. The ocean bottom geomorphology and the fault of Sumatra show several elongated X-shaped structures.

(Bijwaard et al., 1998; Hafkenscheid et al. 2001) show that at a greater depth (200 – 800 km) the high velocity body becomes nearly vertical (Fig. 3b).

The trench is normally interpreted as the site of a mega-thrust whose length is in the order of thousands of kilometers. Indeed in a figure of Ritzwoller et al. (2005) the alleged subducting higher velocity lithospheric slab is bounded towards NE by a defined Wadati-Benioff zone only up to a depth of 200 km. Along this seismofocal surface the plate tectonic theory imagines that a mutual shift occurs between the plunging Indian plate oceanic lithosphere and the backarc lithosphere.

The mechanism of accumulation of potential energy is considered to be purely elastic in a brittle environment. As the Sumatran earthquake was a shallow event, the elastic rebound model can be adopted. The plunging lithosphere moves – with a secular slow rate of few centimetres per year (6.1 cm from NOVEL1 model) – from the surface toward the transition zone and further on (Fig 4a). Friction and asperities stick the backarc lithosphere to the plunging oceanic one allowing them to travel fastened together (Fig 4b) until a fracture starts on the Wadati-Benioff zone (Fig 4c) allowing the backarc lithosphere to rebound elastically toward the surface (Fig 4d), and the subducting lithosphere – without braking – suddenly accelerate.

Certainly this alleged mechanism of earthquake generation is compatible with a sudden upward movement of materials but it should be considered that immediately after the rupture generation, also a sudden downward movement of the 'subducting' slab must occur. Moreover, in a neat secular balance the downward movement of mass would prevail, putting earthquake excitation not in harmony with the secular polar motion.

The focal mechanism

The centroid moment tensor solution of Harvard (Fig. 5a) provides two possible fault plane solutions for the Sumatra earthquake:

P1: Strike = 329; Dip = 8; Slip = 110
P2: Strike = 129; Dip = 83; Slip = 87

The plane solution P1 is the solution adopted by the geoscientists community because it is in good harmony with the allegedly valid geodynamic model – the plate tectonic model. The section of the focal sphere on a vertical plane perpendicular to the strike direction is shown in Fig. 5b.

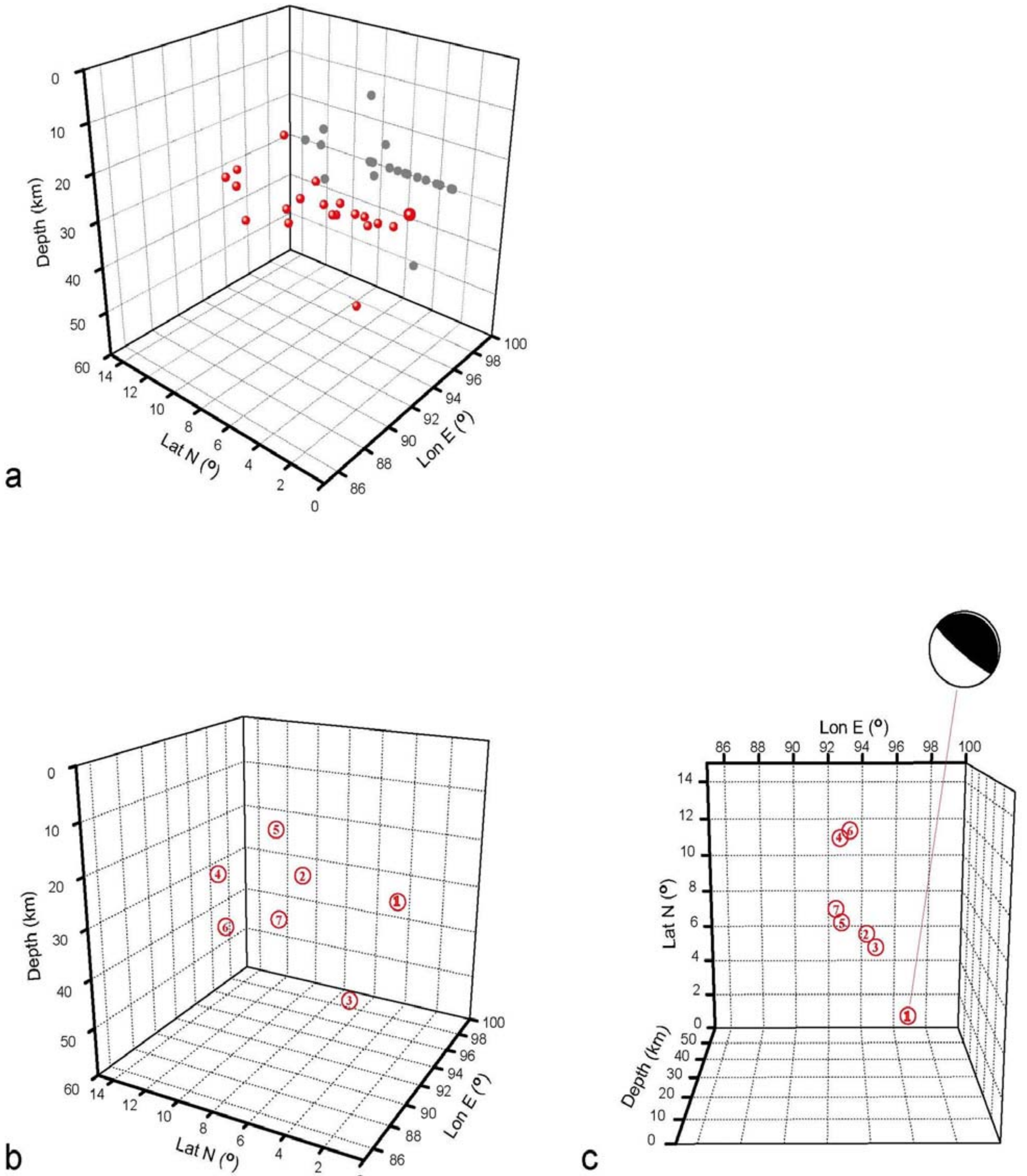

Fig. 8. a) A complete set of hypocenters (20 events; $M \geq 5.5$) which occurred in the first two hours from the main event is shown in red circle. If the hypocenters are projected on the depth-latitude plane (grey circle), it becomes evident the existence of a number of depths fixed at 30 km. The events of this subset are of uncertain depth and also of large uncertainty in latitude and longitude epicentral coordinates. Also the main shock (greater circle) is a member of this subset.

b) The same time and magnitude window is shown after discarding the subset of the 30km-depth data – except the main shock. The total number is decreased to 7 events. The distribution of the hypocenters – numbered chronologically from 1 (main shock) to 7 – is crustal and undercrustal, covering from a minimum of 15 km to a maximum of 51 km.

c) While the plate tectonics expects a distribution dipping northeastward, if we observe the near vertical distribution, it can be seen that it dips slightly to the southwest, rather than along the alleged subduction slab.

The vertical scale in a), b) and c) is exaggerated by more than 10 times, consequently great attention must be paid in judging the dipping angles.

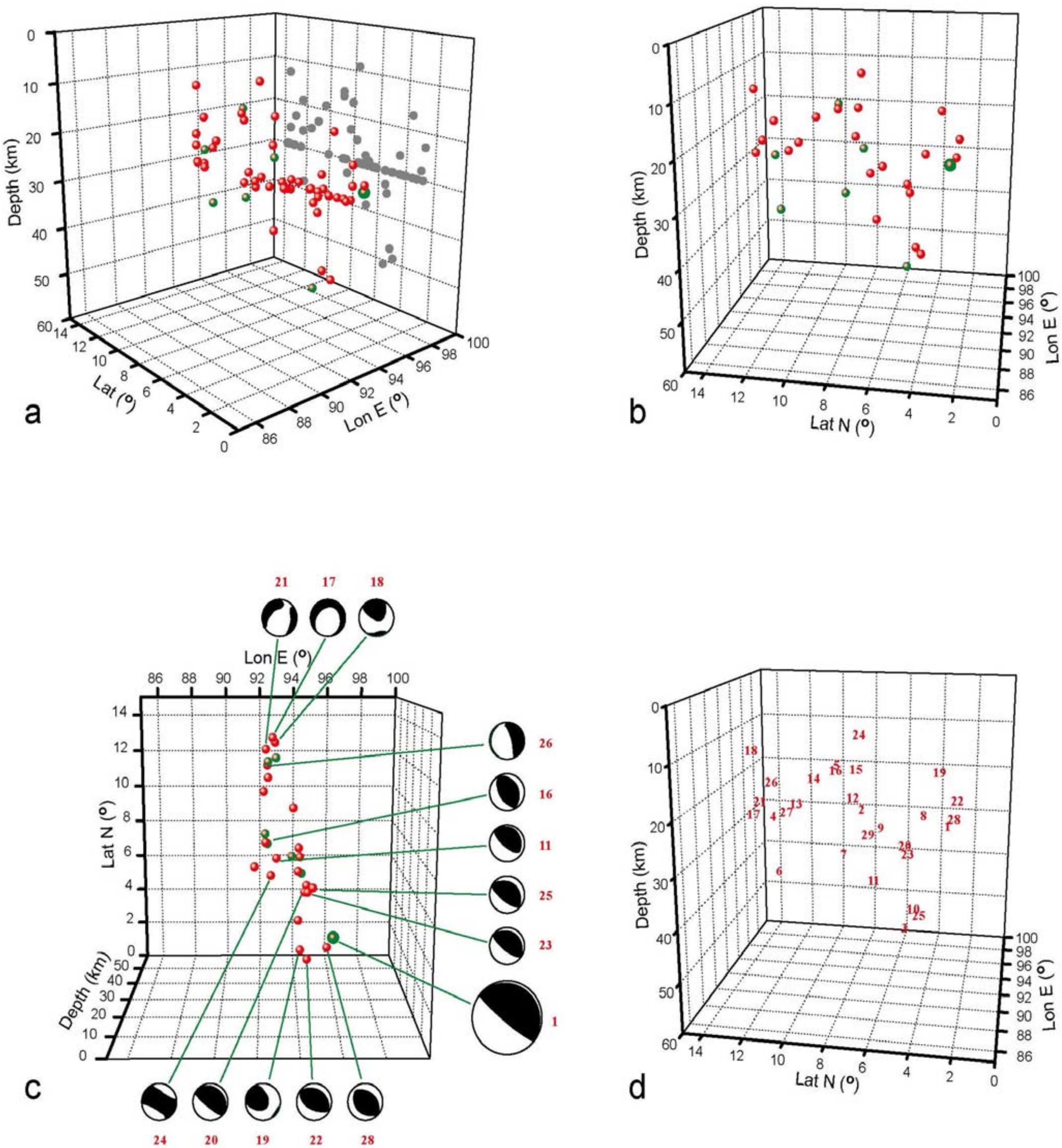

Fig. 9. a) Total number of events (M ≥ 5.5) in the time window of two days (26 and 27 December) is 56 hypocenters (red and green spheres) which are also projected on an ideal latitude-depth plane (grey circles). The green spheres are the seven selected events in Fig. 8.

b) Residual distribution of 29 hypocenters is shown, after the elimination of the events with an assigned depth at 30 km. A small group of hypocenters having depth near 50 km is present near the event number 3.

c) Observing vertically, no definite structure showing a NNE direction of subduction dipping can be seen. Focal mechanisms are also inconsistent with the subhorizontal subduction interpretation. The available Harvard CMT focal mechanisms are numbered following the event numbers in Fig. 9d.

d) In order to facilitate the understanding of the spacetemporal hypocentral pattern, the progressive chronological numbers are shown for the 29 selected events.

The dip angle of 8° has led to speak of a sub-horizontal slip. The value of ≈ 30.0 km has been assigned to the hypocentre depth. The low dip angle, the moderate hypocentral depth and the fault width of 100-200 km lead to a fault plane completely located in the crustal brittle environment. This means that a very high number of large aftershocks would be expected in few hours and days in a large and flat crustal and subcrustal area of approximately 200 × 500 km^2. The distribution of the large (M>6) aftershocks, in the two days after the main shock, was instead very different (see next section).

It is my opinion that a near-horizontal shift of a huge-sized entire region is merely impossible. Long and narrow bars of materials which are undergoing longitudinal horizontal stress and exceeding the rupture limit, should develop thrust fractures through their bodies at dip angles around 45° (see Tarakanov, 2005). A paradox arises and a solution should be searched for checking if the second fault plane P2 – a near vertical plane – has the possibility to fulfil better the observations in a new tectonic and geodynamic model.

The second fault plane solution

The plane solution P2 requires a nearly vertical movement. In this case the rupture plane crosses the entire crust. Referring to Fig. 6, a possible model of rupture evolution – among many other possible but similar ones – can be constructed. In this example, initially (Fig. 6a) a slow process of decoupling of oceanic and continental lithosphere occurs under the arc. Under the effect of this tensional regime the bumping of the arc (Fig. 6a) shows the tendency to subside (Fig. 6b) – this is in accordance with the coral reef subsidence data (Sieh et al., 1999; Zachariasen et al., 1999; Zachariasen et al., 2000; and others). Successively a subvertical fracture (Fig. 6c) is eventually produced by a sudden uplift of undercrustal or underlithospheric material pushed upward by a sudden phase change triggered by the tensional regime. The lifted side can have possibly a downward rebound, producing a tilting of the neighbouring plate (Fig. 6c). This can be in agreement with the observed uplift of the coralline barrier to the west and the subsidence of the larger islands. Finally a plethora of settling new faulting, producing a high number of aftershocks, should be expected (Fig. 6d) diffusely along the entire major fault in a wide area. Lateral spreading of the arc can also be triggered by the main fracture (Fig. 6d).

The model should assume a longer fault length with respect to the P1 solution. This is because an elongated distribution of epicentre of aftershocks Mw ≥ 6.0 has occurred within two hours and two days after the main shock (see the table of the very preliminary epicentres of 26 and 27 December below; see also Fig. 7).

M	Day	Time	Lat	Lon	Depth	
9.0	26/12/2004	0:58:50	3.244	95.825	10	Off the west coast of northern Sumatra
6.2	26/12/2004	1:21:18	6.372	93.363	10	Nicobar islands, India region
6.0	26/12/2004	2:51:59	12.494	92.582	10	Andaman islands, India region
7.5	26/12/2004	4:21:25	6.891	92.891	10	Nicobar islands, India region
6.5	26/12/2004	9:20:01	8.867	92.382	10	Nicobar islands, India region
6.2	26/12/2004	10:19:30	13.455	92.791	10	Andaman islands, India region
6.3	26/12/2004	11:05:01	13.542	92.877	10	Andaman islands, India region
6.2	26/12/2004	19:19:53	2.770	94.158	10	Off the west coast of northern Sumatra
6.0	27/12/2004	0:32:13	5.502	94.465	10	Northern Sumatra, Indonesia
6.1	27/12/2004	0:49:27	12.978	92.449	10	Andaman islands, India region
6.1	27/12/2004	9:39:03	5.379	94.706	10	Northern Sumatra, Indonesia
6.0	27/12/2004	10:05:00	4.762	95.111	10	Northern Sumatra, Indonesia

(USGS preliminary data; released on 29 December, 2004)

If the real fault plane was the P1 horizontal solution, one would expect an immediate activation of the entire alleged fault surface (see rectangular boundary in Fig. 7). However, this fault surface has not shown the expected immediate high-magnitude aftershock activity and this fact constitutes a strong clue favouring the vertical fault solution P2 which is extending more than 1200 km from west Sumatra to northern tip of Andaman Islands (see the bold dotted line in Fig. 7). In this very region occurred the expected series of aftershocks. It should be noted that the fist aftershock (Mw=6.2 T=1:21:18; Lat=6.37 Lon=93.36) was at more than 3° north of the main shock and the second aftershock (Mw=6.0 T=2:51:59; Lat=12.49 Lon=92.58) more than 9° north of the main event; these events occurred within 2 hours. The elongated space window and a narrow time window are strongly in favour of a true nature of aftershock of these events on the same long structure.

The elongated figure of the fault is supported also by simple analysis on the length of the high frequency P-wave record on seismograms (Lomax, 2005; Lomax and Michelini, 2005). The P-wave radiation has had duration compatible with a fault rupture propagation of at least 1100 km. The NNW directivity of initial propagation is assured by the characteristic different length and frequency – Doppler Effect – of the P wave train recorded at different azimuths (Bilham, 2005; Ishii et al., 2005).

Inconsistency of the plate tectonic-biased P1 solution has not been recognized in a series of papers dedicated to the Great Sumatra Earthquake. However, the need for a steeper slip plane was claimed by the analysis of the normal mode by Park et al. (2005).

The USGS preliminary hypocentres data and the Harvard CMT catalogue

I have extracted the data from the USGS global seismic catalogue with the further aim to inspection the 3-D distribution of the preliminary hypocenters. The extractions of the data have been sectioned at two hours from the origin time of the main shock, and at two days, and at the end of February 2005. But I have concentrated my interest on the first two shorter time windows, because I believe that a seismic event (*sensu lato*) is better characterized by what happened immediately after the occurrence of the main shock.

The data from 26 December, 00h 00m 00s, to 27 December, 24h 00m 00s, are listed in Table 1, and the selected events are chronologically numbered. Asterisks indicate events that have a CMT fault solution in the Harvard catalogue. Double asterisks indicate the CMT solutions plotted in Fig. 9c.

All the extracted sets of data show subsets of high number of earthquakes whose depth has been fixed to 30 km. I have considered these subsets as data not having a sufficient control on depth and I preferred to remove them in the figures I discuss, because these data can produce an erroneous confidence in a prevailing horizontal pattern.

In Fig. 8a a complete set (20 events) of hypocenters ($M \geq 5.5$) which occurred in the first two hours from the main event is shown as a red circle. The projection of the hypocenters on the XZ plane (grey circle) shows more clearly the existence of a number of depths fixed at 30 km than in the 3D distribution. The subset of these events is not only of uncertain depth but, as consequence of an odd computation, also of large uncertainty in latitude and longitude epicentral coordinates. Also the main shock (larger red sphere in Fig. 8a) is a member of this subset. The cause of this computational difficulty is the same that made impossible to determine the focal mechanisms for nearly all the aftershocks up to the middle of 26 December. In Fig 8b the same time and magnitude window is shown without the subset of the 30km-depth data – except the main shock, and then the total number is decreased to seven events.

The distribution of the seven hypocenters – numbered from 1 (main shock) to 7 – is crustal and undercrustal, covering from a minimum of 15 km to a maximum of 51 km. The depth scale is exaggerated by more than 10 times. While the plate tectonics expects a distribution dipping to northeast, if we observe the distribution nearly vertically (Fig. 8c) it can be seen that it dips slightly to the southwest, rather than along the alleged subduction slab.

I repeated the same type of plotting, discarding the 30km depth events, using a time window lasting for two days (26 and 27 December). In Fig. 9a the total number of events, 56 hypocenters, is shown beside their projection on the XZ plane. The 56 events are listed in Table 1. After the elimination of the events with an assigned depth of 30 km, the residual distribution of 29 hypocenters is shown in Figs. 9b and 9c. No definite structure in accordance with a NNE direction of subduction dipping is present in these events. In Figs. 9a-c a small group of hypocenters having a depth near 50 km is spotted near the event number 3 in Figs. 8b & c. In Fig. 9d, in order to facilitate the understanding of the spacetemporal hypocentral pattern, the progressive chronological numbers are shown for the 29 selected events.

Moreover, the various focal mechanisms – which are numerous starting from the second half of 26 December – which should reveal the fault orientation and sense of motion on the fault are also inconsistent with the subhorizontal subduction interpretation. The available Harvard CMT focal mechanisms indicated around Fig. 9c are numbered following the event numbers of Fig. 9d.

The seismic moment

The definition of seismic moment is:

$$M_o = \mu \cdot s \cdot A \qquad (3)$$

with μ the shear modulus of the material, s the mutual dislocation of the two side of the fault, A the area of the fracture surface. The magnitude-moment is defined upon the seismic moment:

$$M_w = \frac{2}{3}\log_{10} M_o - 10.7 \qquad (4)$$

The longest period normal modes of the earth, ${}_0S_2$ and ${}_0S_3$ – analyzed by Stein and Okal (2005) – yield a moment M_o= 1.3 $\cdot 10^{30}$ dyn·cm, three times larger than M_o= 4.0 $\cdot 10^{29}$ dyn·cm evaluated from long period surface waves. Then, from (4) an earthquake's ultra-long period magnitude, M_w = 9.3, results, which is significantly larger than the previously reported M_w = 9.0.

The fact that the ultra-long period moment is higher than that from the 300-s surface waves used by the Harvard CMT project reflects a significant physics process we misunderstand. The interpretation of the Stein and Okal (2005) – toward which the scientific community converges – is that a several meters fast slip occurred only on the southern 1/3 (around 400km) of the sub-horizontal fault, and then only this 1/3 of the total length of the fault is responsible of the long period surface wave excitation, while a slower slip occurred on the northern 2/3 of the interested structure exciting mostly the normal mode of the Earth.

Instead, in my opinion, the discrepancy between surface wave M_o and normal modes M_o should be considered an important anomaly – in a sense of Khun (1969) – whose clarification could lead to a substantial transformation of our view about the Earth's composition, processes and evolution. Here I search for a solution by adopting the near vertical slip plane of the conjugate P2 fault solution instead of following plate tectonics prescriptions.

Indeed, assuming an average rigidity of 5.0 $\cdot 10^{11}$ dyn/cm^2 (see table A.3 in Bullen and Bolt, 1985), 15 m of slip – on the nearly vertical P2 fault solution – on a fault 1200 km long and 50 km deep (the maximum depth of a brittle fracture) implies a moment of about 4.5 x 10^{29} dyn·cm

$$M_o = \mu \cdot s \cdot A = 5.0 \cdot 10^{11} \text{ dyn/cm}^2 \cdot 1.5 \cdot 10^3 \text{ cm} \cdot 1.2 \cdot 10^8 \text{ cm} \cdot 0.5 \cdot 10^7 \text{ cm} = 4.5 \cdot 10^{29},$$

which is in accordance with the M_o measured using the long period surface waves. With the adoption of the previous new fault parameters P2 there is no need to limit the slip zone to the southern 1/3 of the aftershocks zone. The apparent excess seismic moment deducible from the ${}_0S_2$ and ${}_0S_3$ modes (Stein and Okal, 2005) should be considered as a fictitious phenomenon linked to a large amount of energy release not through an 'elastic rebound' process but as a sudden displacement of materials – presumably a vertical displacement – that has caused the strong ${}_0S_2$ and ${}_0S_3$ excitation, the destructive tsunami, and the Earth's instantaneous rotational pole displacement. This vertical displacement should have bulged the belt zone interposed between the Sunda Trench and the proposed rupture line (Fig. 7).

An analogy can be envisaged between the mass movement occurred during the Sumatran event and the process that leads to a percentage of volcanic earthquakes to have their spectra displaced toward the low frequencies. These volcanic earthquakes are more destructive than destructivity inferred from Mb, and only Mw – computed on lower frequencies – provides a more realistic estimate of their energy. The process involved in this kind of volcanic events could be hypothesized as – to propose only an example among many – a laccolite emplacement.

Oceanographic sea-level variation data and hypothesized geoid variations

The published preliminary results of the Geographic Survey Institute of Japan show the postseismic level variations of the coast of the entire region. Data are provided by satellites Radarsat-1, Envisat, ERS-1/2, Aster, Spot-5, updated to March 10, 2005. The coralline barrier – located to west – has been uplifted by the earthquake. Andaman Islands and parts of north-west coast of Sumatra subsided. This is in agreement with the preferred framework of this paper, and is also supported by the geoid variations forecasted by Sabadini et al. (2005) and many others. The geoidal pulse is not substantiated by the commonly accepted P1 fault plane solution CMT of Harvard.

The web site of Bilham – http://cires.colorado.edu/~bilham/IndonesiAndaman2004.htm – reports further geodetic results in complete agreement with the postseismic level variation revealed by the satellites.

Several studies have been made about the past and present state of emergence and submergence of coral microatols (Sieh et al., 1999; Zachariasen et al., 1999; Zachariasen et al., 2000; and others). The interpretation of the data converges on a cyclic uplift and subsidence derived from the coral ring studies and the most authors agree to the applicability of the plate tectonic model in Fig. 4. However, some authors obviously did not well understand the evidence of sudden paleo-subsidence.

In Fig. 7 the uplifted and subsided zones reported by the Japanese GSI are shown in red and yellow, respectively. The proposed vertical rupture line (bold dotted line) is the divide between the bulged and the subsided zones. The ophiolites typical of huge formation of Nicobar and Andaman Islands (Coleman, 1977) are further evidence of a steady uplift of the arc in the geologic time with different rates of emergence along the Sunda Arc.

In the framework proposed in this paper the sudden subsidence is well explained as part of the process of vertical fracture of the crust (Fig. 6).

Concluding remarks

The multi-faceted problem of the discrepancies in the seismic moment of the great Sumatra earthquake led to the conclusion that the alleged plate tectonics subductive process cannot be invoked as cause of the observed phenomena. This is in agreement with Choi (2005) who based his arguments on seismic profile, earthquakes, regional geological and seismo-tomographic data. The following conclusions can be drawn on the basis of the available data as discussed above:

1) The Matera Observatory SLR observations on the polar motion shift that has followed the Sumatra main shock are in support of a geodynamics of the Wadati-Benioff zone in accord to the interpretation of Scalera (2004 & 2005b), in which an upduction of mantle material – upward displacement of materials – is responsible of the tectonic phenomena on the trench, arc and backarc zones.

2) The subhorizontal fracture of 500 × 200 km^2 is not favoured by data, because the true sequence of stronger aftershocks occurred in the first few hours after the main event has defined a linear arched structure with a length up to 1200 km. The broader distribution of subsequent aftershocks has been caused possibly by a diffuse fracturing of the crust and dikes and/or laccolites emplacements around the main fault. The P-wave train propagation and duration are in favour of this interpretation.

3) Pure near vertical dislocation is in good accordance with the oceanographic data of sea level variation, hypotheses for the geoid variation, and other geodetic results.

4) The second conjugate CMT fault plane solution (P2: Strike= 129; Dip= 83; Slip= 87) is the most likely real solution because it fulfils the need for vertical displacement, and it can be

put in good accord with the observed data of PM and seismic moment.

5) The excess of seismic moment – measured for analyzing the spectral amplitude of the $_0S_2$ and $_0S_3$ Earth's normal modes (Stein and Okal, 2005) – is presumably fictitious. The excess could be linked to a larger amount of energy released not in an 'elastic rebound' process, but as a vertical displacement of mantle materials that has caused the strong $_0S_2$ and $_0S_3$ excitation, the destructive tsunami, and the Earth's instantaneous rotation pole displacement.

6) The main discriminating factor in the real direction of mass displacement is obviously the sudden effect on the length of day (LOD) (few microseconds, today under the level of the observational errors; Chao and Gross, 2005), and great effort should be dedicated to the improvement – to gain one or two order of magnitude – of the time measurement methodologies. The effect must be an increase of the LOD and not a decrease as prescribed by models (Chao and Gross, 2005) using plate tectonics kinematics.

7) The cause of this vertical displacement is not known, and only hypotheses can be actually proposed. Changes of phases starting from a metastable state in a wide region of the upper mantle driven by local decompression under the trench due to global expansion can be envisaged, but many other possibilities exist.

8) The frequency of great earthquakes on the Sunda arc and the actual and historical vertical displacements lead to the conclusion to be in presence of the initial processes involved in mountain building. Indeed, modern views on orogenic processes (Ollier, 2003) stress the age of a few million years of the actual uplifted mountain system. The Sunda Arc is expanding toward the ocean without encountering large obstacles, therefore the uplift will be presumably little. Where the expanding arc finds a large obstacle, like Himalayan arc against India, the heights could be greater.

9) A revision of the interpretation of the real nature of the largest earthquakes in this and the past centuries should be undertaken. A close examination of the phenomena which accompanied the 1926 Aleutian, the 1957 Aleutian, the 1960 Chile, and the 1964 Alaskan earthquakes should be performed, tabulating the analogies among them.

10) To ascertain the true nature of the global strong seismicity is not a research of pure academic interest. It is a fundamental research and as such it has strong links to the everyday life, social and economic development and civil protection. Indeed, there will be no hope to improve (if any) or to inaugurate methodologies of earthquake forecasting if a wrong earthquake mechanics model was adopted at a starting point of the inference chain. Responsible consideration should then be made by the scientific community and civil protection institutions on the possibility to start new lines of research on earthquake forecasting, starting from assumptions different from the plate tectonics models. Ideas on energy transmigration like those expressed by Blot & Choi (2004) should deserve a new appraisal by the Earth science communities.

These considerations give support to a number of other global tectonic hypotheses that can work without subduction, and an expanding Earth (Scalera, 2003; Scalera and Jacob, 2003) is among them. A confirmation of these considerations will come by repeated observations on future large earthquakes and from reinterpretation of the old strongest seismic events of the last century.

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TABLE 1

DAY	ORIG TIME h m s	LAT (°)	LONG (°)	DEPTH km	MAG	N°
26	005853,45	3,30	95,98	30	9,0 Mw**	1
26	011710,33	4,94	94,27	30	5,5 mb	
26	012120,66	6,34	93,36	30	6,1 mb	
26	012225,59	7,42	93,99	30	6,0 mb	
26	012548,76	5,50	94,21	30	6,1 mb	
26	013015,74	8,83	93,71	30	5,5 mb	
26	013322,38	7,76	93,71	25	5,5 mb	2
26	014852,07	5,43	94,46	51	5,7 mb	3
26	020040,03	6,85	94,67	30	6,0 mb	
26	021523,57	6,17	93,47	30	5,6 mb	
26	021559,78	12,32	92,50	26	5,7 mb	4
26	022201,84	8,87	92,47	15	5,7 mb	5
26	023452,15	3,99	94,14	30	5,7 mb	
26	023610,09	12,18	92,94	38	5,8 mb	6
26	023809,35	8,49	92,35	33	5,6 mb	7
26	024620,74	4,24	93,61	30	5,7 mb	
26	025201,83	12,50	92,60	30	5,8 mb	
26	025914,39	3,18	94,38	30	5,7 mb	
26	030238,08	8,61	92,33	30	5,5 mb	
26	030844,21	13,74	93,01	30	5,9 mb	
26	031752,38	7,21	92,92	30	5,6 mb	
26	031913,05	3,55	94,29	30	5,5 mb	
26	032454,94	4,47	94,07	26	5,8 mb	8
26	034015,64	5,53	94,33	30	5,6 mb	
26	035112,36	5,05	94,77	30	5,7 mb	
26	040058,43	6,79	94,08	29	5,5 mb	9
26	040255,73	4,98	94,72	47	5,8 mb	10
26	042129,81	6,91	92,96	39	7,5 Ms**	11
26	060228,38	8,27	94,06	23	5,7 mb	12
26	065647,40	10,98	92,28	23	5,5 mb	13
26	070710,27	10,36	93,75	19	5,6 mb	14
26	073827,00	13,13	93,04	30	5,7 mb	
26	075228,80	8,13	94,07	17	5,5 mb	15
26	092001,61	8,88	92,38	16	6,6 Ms**	16
26	101813,79	8,86	93,74	30	5,5 mb	
26	101931,73	13,46	92,74	26	6,1 mb**	17
26	105119,82	7,63	92,31	30	5,5 mb	
26	105602,59	10,07	93,83	30	5,5 mb	
26	110500,72	13,53	92,84	13	6,3 mb**	18
26	135640,17	2,78	94,47	30	5,9 Ms*	
26	144844,26	13,59	92,91	30	5,8 mb*	
26	150633,24	3,65	94,09	17	6,1 Ms**	19
26	190349,21	4,09	94,22	30	5,5 mb	
26	191955,57	2,79	94,16	30	6,2 Ms*	
26	210648,80	4,47	96,34	30	5,5 mb	
27	003216,48	5,48	94,47	33	6,0 mb**	20
27	004928,59	12,98	92,39	23	6,0 mb**	21
27	074735,40	2,71	94,51	23	5,6 Ms**	22
27	083738,47	6,48	93,28	30	5,7 Ms*	
27	093906,80	5,35	94,65	35	6,2 mb**	23
27	095752,73	7,71	92,64	9	5,7 Mw**	24
27	100505,44	4,72	95,11	49	5,9 Mw**	25
27	144646,49	12,35	92,47	19	5,8 mb**	26
27	191318,85	11,59	92,50	25	5,5 mb	27
27	201051,31	2,93	95,61	28	5,8 Ms**	28
27	202344,61	7,06	91,79	28	5,7 Mw	29

Table 1. The 56 seismic events (M ≥5.0) occurred from 00h 58m 26 December, 2004 to 24h 00m 27 December 2004. They are plotted in Fig. 9a. The 29 events with a better defined hypocentral depth are numbered in chronologic order, and they are plotted in Fig. 9bcd. The events which have a focal mechanism in the CMT-Harvard catalogue are labelled with asterisks. Double asterisks indicate that the focal mechanism is plotted in Fig. 9c.

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