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THE SEISMOGENIC POTENTIAL OF THE SUBDUCTION ZONES – THE TWO GREAT EARTHQUAKES: CHILE (Mw8.8, 2010) AND SUMATRA (Mw9.1, 2004) – INDICATORS ABOUT SUDDEN PLATE MOVEMENTS

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ABSTRACT. The comparative analysis about the two strong earthquakes near continental plate boundaries – Indian and Sunda plates (Sumatra Island-Indonesia) and South America and Nazca plates (Chile coast) is made concerning their seismogenic potential. In the frame of the recent geotectonics, epicenter and hypocenter positions, depths of the seismic events, rupture process and the other parameters considered the explanation about the plate movements is outlined. The first giant earthquake (Mw9.1) generated a huge transatlantic tsunami, which kills more than 200 000 people in many countries around the Indian Ocean, thus appeared one of the greatest catastrophes during the mankind history. The second one (Mw8.8), located to the Chilean east coast produced a very small tsunami (which is absolutely unusual for such size of magnitude), but brought large destructions and more than 1000 deaths on the coastal cities. To know the potential of the subduction seismic zones to produce huge earthquakes able to move suddenly continental plates or parts of them appears of essential importance in view of the recent geodynamics. The geodesy data and information is of primary importance to asses the limitations due to the underwater sources of the earthquakes. The huge areas and volumes of earth's crust destruction delineated by a sequence of the very powerful and numerous aftershocks can help to understand the destructive processes - their size and generic potential.

СЕИЗМОГЕНЕН ПОТЕНЦИАЛ НА СУБДУКЦИОННИТЕ ЗОНИ – ДВЕ ГОЛЕМИ ЗЕМЕТРЕСЕНИЯ: ЧИЛИ (М8.8, 2010) **И СУМАТРА** (**М**9.1, 2004) – **ИНДИКАТОРИ ЗА ВНЕЗАПНИ ПЛОЧОВИ ДВИЖЕНИЯ**

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РЕЗЮМЕ. Направен е сравнителен анализ между две от най-силните земетресения регистрирани напоследък на Земята и разположени в близост до конвергентните граници на плочите: Индийската и Сунда (в района на о-в Суматра) и Южноамериканската и Наска (по крайбрежието на Чили). В светлината на съвременната геодинамика, положението на епицентрите и хипоцентрите им, процесите на разкъсване на земната кора и други данни е потърсено обяснение на относително бързите движения на континенталните плочи или части от тях. Първото грандиозно земетресение (Mw9.1, 2004) генерира огромни вълни цунами, които погубиха над 200 000 души в много страни около Индийския океан, явявайки се по този начин едно от най-катастрофалните събития сполетели човечеството през цялата му история. Второто гигантско земетресения (Mw8.8, 2010) разположено в близост до Чилийското крайбрежие, генерира относително малки вълни цунами (явление абсолютно необичайно за подобни по сила земетресения), но предизвика тежки разрушения и повече от 1000 жертви в крайбрежните селища. За определянето на сеизмогенния потенциал на субдукционните зони да генерират много силни земетресения е от съществена важност да се оценят ограниченията лимитиращи геодинамичната активност на подводните земетръсни огнища. Огромни площи и обеми от континенталната разрушена земна кора са очертани от поредица силни следтрусове, които помагат за определянето на размерите им. GPS измервания, показват размерите на премествանията, регистрирани в околностите на тези силни земетресения.

Introduction

The seismogenic potential of the subduction zones is the largest one according the planet's geodynamics. Almost all great earthquakes (especially with the moment magnitude larger then 8.5) are closely related to the subduction zones. The plate movements in these zones are most active, constant temporal displacements reaching 6-7 cm/y and thus they are responsible about the stress accumulation and the following giant earthquakes.

The seismicity of the subduction zones is studied in the relation of the two very strong earthquakes – the Sumatra one (on 26th December 2004, My~9.1) and the Chile one (February 27th 2010, Mw~8.8) and their tsunamigenic potential. The first dangerous event (a couple of earthquake and tsunami) had heavy consequences and more than 200 000 fatalities. The second one – with relatively small tsunamis with no victims, produced about 1 000 deaths as a consequence mainly due to the earthquake effects to the buildings of the Chile coastal area.

Both events were related with the stress release and movements of the plates in the subduction zones – Nazca plate subducting South American continental plate (for the Chilean quake) and Sunda trench collision zone (for the Sumatra seismic event). In general this oceanic plate subducted thicker continental plate. Due to this collision the stress field in the whole contact zone between the two plates increased and generated huge seismic events which can produce the large displacement, especially measured on the upper plate. This process is accompanied by the temperature increase, volcanic activity in deeper parts, crust and astenosphere deformations, orogenic effects and deep trench creation (Fig. 1). The rebound effect expressed frequently like megathrust seismic events almost always generate tsunami waves (Murty, 1977).

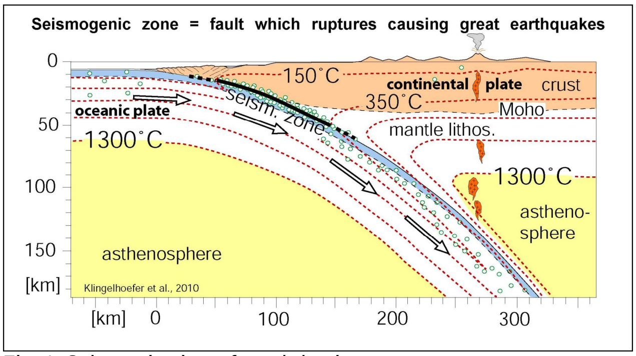

Fig. 1. Schematic view of a subduction zone

Tectonic setting

The region where the great earthquake occurred on 26 December 2004, marks the seismic boundary formed by the movement of the Indo-Australian plate as it collides with the Burma subplate, which is part of the Eurasian plate. However, the Indo-Australian tectonic plate may not be as coherent as previously believed. According to recent studies it appears that the two plates have separated many million years ago and that the Australian plate is rotating in a counterclockwise direction, putting stress in the southern segment of the India plate. For millions of years the India tectonic plate has drifted and moved in a north/northeast direction, colliding with the Eurasian tectonic plate and forming the Himalayan Mountains. As a result of such migration and collision with both the Eurasian and the Australian tectonic plates, the Indian plate's eastern boundary is a diffuse zone of active seismicity and deformation, characterized by extensive faulting and numerous large earthquakes.

The epicenter of the 26 December 2004 earthquake was near the triple point junction of three tectonic plates where major earthquakes and tsunamis have occurred in the past. Previous major earthquakes have occurred further north, in the Andaman Sea and further South along the Sumatra, Java and Sunda sections of one of the earth's greatest fault zones, a subduction zone known as the Sunda Trench. The great Sunda trench extends for about 3400 miles (5500 km) from Myanmar (Burma) south past Sumatra and Java and east toward Australia and the Lesser Sunda Islands, ending up near Timor. Slippage and plate subduction make this region highly seismic. The Burma plate encompasses the northwest portion of the island of Sumatra as well as the Andaman and the Nicobar Islands, which separate the Andaman Sea from the Indian Ocean. Further to the east, a divergent boundary separates the Burma plate from the Sunda plate.

More specifically, in the region off the west coast of northern Sumatra, the India plate is moving in a northeastward direction at about 5 to 5.5 cm per year relative to the Burma plate. These data have been inferred by the GPS measurements and observations (http://walrus.wr.usgs.gov/news/reports.html).

The Chile 27 January 2010 great seismic event is located over the edge of the subduction zone of Nazca plate subducted under the South America continental plate at the approximately mid location of the Chile Ands. The subduction in the area started several million years ago and the low destruction of the oceanic crust succeed to subduct in more then 3-400 km inland reaching one of the known most deep parts of the mantle. The deepest earthquakes of this plate are expressed down to 600-700 km. thus producing great events like Bolivian one of 9th June, 1994 year (Mw~8.0) felt from Antarctica to New York. The GPS measured horizontal velocities of the South American plate move to the west are measured of about 6-7 cm (it is better to say that the subducted Nazca plate has such velocity of east movement). The Peru-Chile trench is the frontal boundary of the subduction and it is confirmed by the hypocenters location of the earthquakes in the area (http://earthquake.usgs.gov).

Data about the earthquakes

The 26th Boxing Day 2004 earthquake occurred with a starting point of the hypocenter located at 3,316°N; 95,854°E. The reported mechanism by the Harvard tensor moment solution was thrust type. Then the ruptured process has extended to the North for about 10 minutes and according different models the area of the surface dislocations covered more than 337500 sq. kilometers. The depth reached 33 km. The initial aftershock's behavior confirmed this direction of dislocation. Almost two-three months after the main event, all aftershocks covered the north part of affected area (Fig. 2). The thrust type mechanism, the great magnitude, large area of surface deformations, the activation of the underwater deposits slides and the displaced water volume are the main factors leaded to the giant tsunami spread across the Indian Ocean and brought so much victims and destructions.

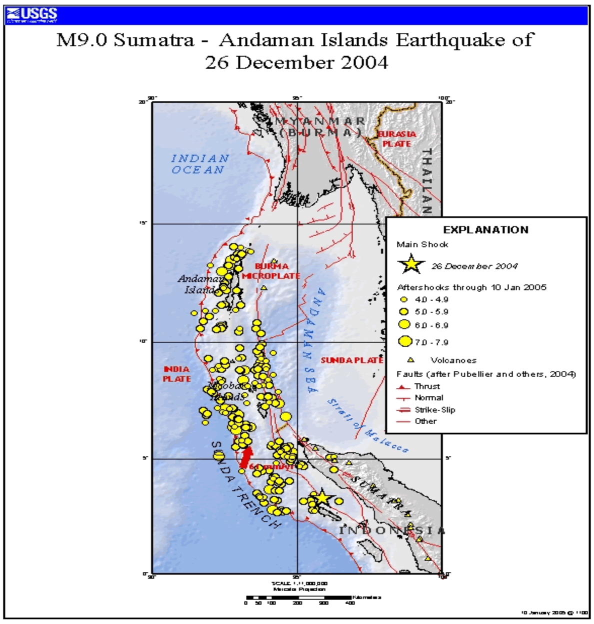

Fig. 2. The location of the epicenters due to the 26th Dec.2004 seismic event. Ruptured zone is outlined by the yellow circles of some aftershocks distribution, according their tectonic positions

The earthquake of February 27, 2010 (M~8.8, depth down to 30 km), was probably triggered by the dynamic stress load caused by collision of South America and Nazca plates. The January 27th earthquake occurred – as a result of thrust faulting – on the boundary of the Nazca and South America plates (Fig. 2). It was caused by the release of stresses when the Nasca plate subducted beneath the overriding South America plate. This interaction results in convergence at the Chile Trench and involves local movement, with a total area of displacement of about 0.5 km^2. The shock was located to the North of the ruptured area of the strongest recently recorded seismic event of 1964 with the largest magnitude of Mw~9.5 (Fig. 3; http://earthquake.usgs.gov).

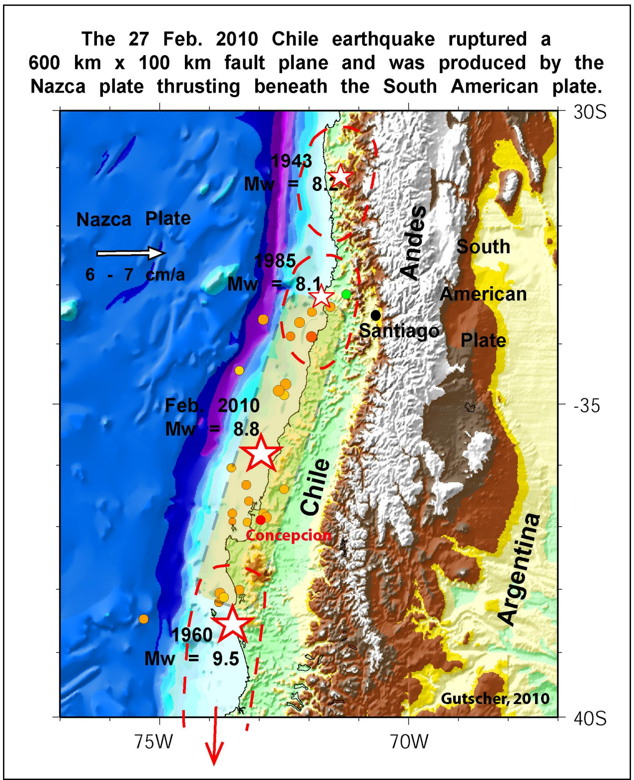

Fig. 3. The strongest subduction earthquakes near Chile coast

The historical and recent Chilean strong earthquakes (http://www.emsc-csem.org/):

- October 28, 1562. This was magnitude 8 earthquake and its epicenter was at 38.0 S, 73.5 W. It generated a destructive tsunami with 16 meter maximum run-up height.
- February 8, 1570. This earthquake occurred in the same general area of Central Chile (epicenter 37.0 S, 73.0 W) but its magnitude was estimated to be even greater, at 8.8. The maximum tsunami runup height was 4 meters.
- December 16, 1575. This was an extremely severe earthquake in Southern Chile with source characteristics very similar to the May 22, 1960 event – which occurred centuries later in the same region. Its estimated epicenter was at 40.0 S., 70.0 W. Its strong aftershocks continued for a period of forty days. Almost immediately after the quake tsunami waves reached Valdivia, 25 km up the river by the same name, reversing its flow, is destroying houses, uprooting trees and sinking two galleons at the port. Along the coast of La Imperial, north of Valdivia, the tsunami killed 100 people. Landslides from the quake blocked the flow of a river flowing into lake Rinihue. A subsequent break of the dam killed 1200 people.
- March 15, 1657. Its epicenter was at about 37.0 S., 73.0 W. Its magnitude estimated at 8.0. It generated a tsunami with a maximum height of 8.0 meters.
- November 19, 1822. This was a large earthquake with epicenter at 33.0S. 71.4W, and an estimated magnitude of 8.5, which caused considerable destruction in Central Chile and generated a destructive tsunami with a height of 3.5 meters.
- February, 1835. A tremendous earthquake occurred, described well by the captain of the Darwin's Beagle ship.
- May 10, 1877. Two large earthquakes near Africa, on May 9 and May 10. The May 9 event had its epicenter at 21.6 N.71.0W and its magnitude was 8.5. It generated a destructive tsunami of 16 meters in Northern Chile. The second one, which occurred day later on May 10, had an estimated magnitude of 8.3. Its epicenter was at 19.6 S., 70.2 W.
- August 17, 1906. The epicenter of this quake was at 33.0 S., 72.0 W. This was a large shallow magnitude (8.6) tsunamigenic earthquake with epicenter near that of the 1822 event and approximately 300 km to the north of the February 27, 2010 event. The quake caused destruction in Chile and generated a tsunami that was destructive locally and at distant locations.
- November 27, 1922. Date given as November 21, 1927 and epicenter at 44.6 S, 73.0 W. This was a very destructive earthquake with magnitude of 8.5 which occurred approximately 870 km to the north of the February 27, 2010 event. The quake was extremely destructive along central Chile, causing several hundred fatalities and severe property damage. It generated a destructive 9-meter local tsunami that inundated the Chile coast and was particularly damaging along the coastline near the town of Coquimbo. The tsunami impacted Hawaii, washing away boats at Hilo harbor.
- May 22nd ,1960 (Magnitude 9.5). The largest earthquake in the world – approximately 1655 killed, 3000 injured, 2000000 homeless, and $550 million damage in southern Chile; tsunami caused 61 deaths, $75 million damage in Hawaii; 138 deaths and $50 million damage in Japan; 32 dead and missing in the Philippines; and $500000 damage to the west coast of the United States.

The comparison with the aftershocks distribution about Sumatra earthquake (Fig. 2) shows much larger area covered. This is reasonable having in mind that the Sumatra event had much larger magnitude then the Chilean one. Both distributions outline the sizes of the seismic sources, where the Earth crust destruction and stress release took place.

A comparative analysis

Triple junction points of tectonic plates, particularly in areas of active subduction, are some of the most seismic areas of the world – capable of causing great earthquakes and tsunamis. The 1960 Great Chilean Earthquake and Tsunami originated near such a triple point tectonic junction.

The same is valid about 26th Boxing Day 2004 great Sumatra earthquake and 27th February Chilean event. Usually, when a great earthquake occurs, most of the stress is relieved and another great earthquake may not occur for many years in the

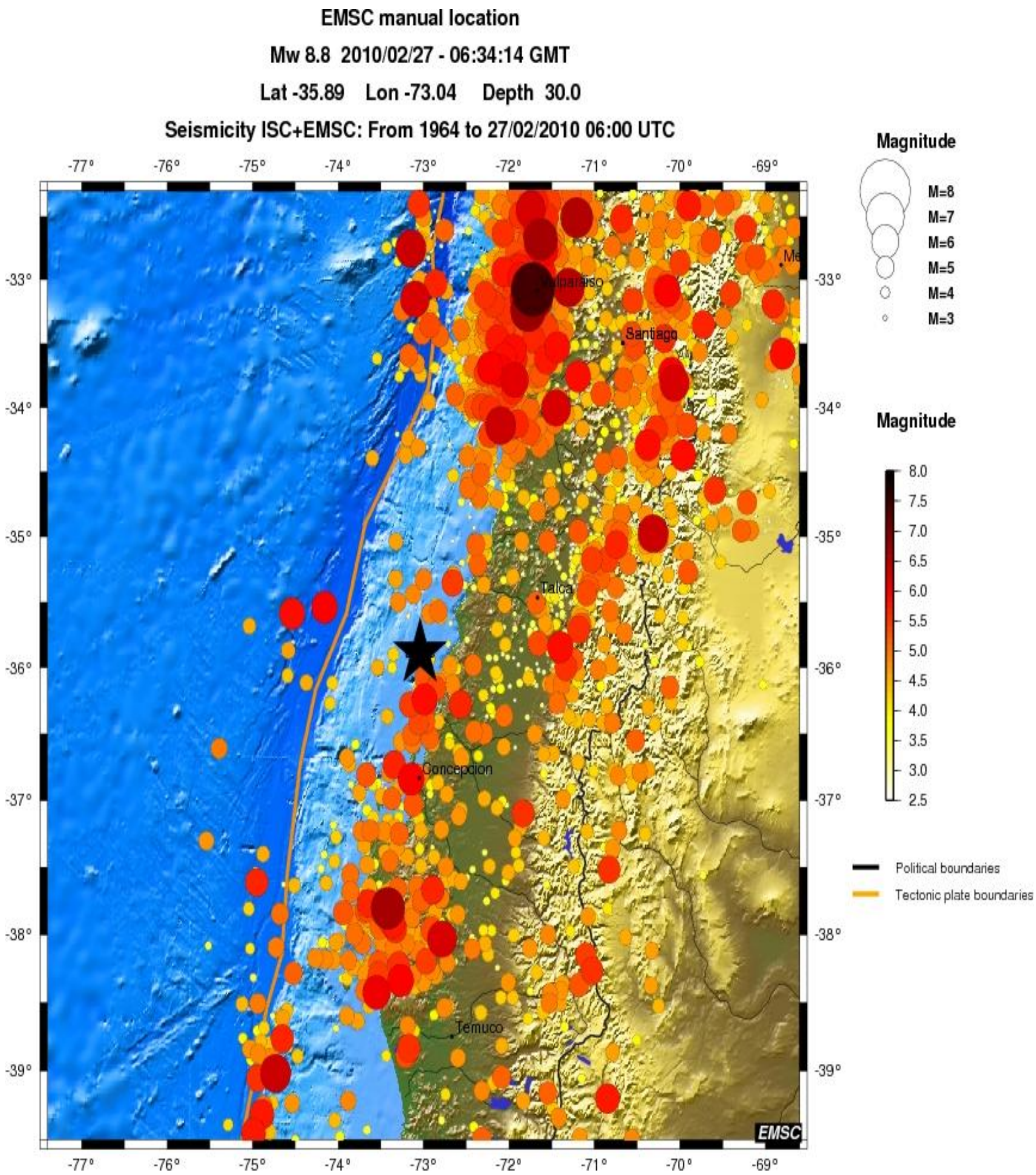

Fig. 4. Regional seismicity around the 27.02.2010 Chile earthquake (star) since 1964 (acc.http://www.emsc-csem.org/)

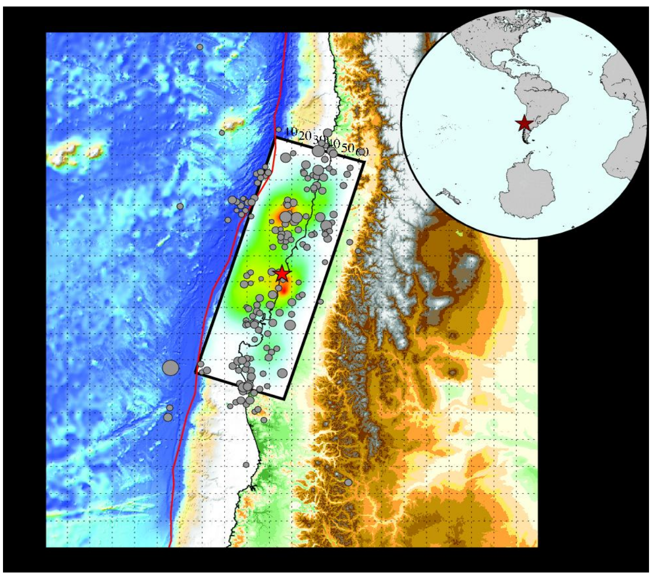

Fig. 5. Some aftershocks locations about the Chile seismic event

same region. However, this is not always the case, as dynamic stress loading can accelerate the occurrence of another major earthquake along an adjacent seismic zone. Sometimes the opposite occurs and the release of energy on one segment, may also release stress on an adjacent seismic fault. In this case it looks like that the stress release process was accelerated rather than delayed.

The summary of all investigated parameters have been presented at Table 1. Both seismic events have very similar characteristics (magnitude, depth, mechanism type). The differences are connected mainly to the ruptured areas (length, width, vertical displacements), average water depth, the supposed underwater slides and the tsunami parameters – maximum observed run ups and the displaced water volumes. It is visible that the maximum run ups Hmax are of one order difference and the displaced water volumes have the same

Table 1. Main characteristics of both earthquakes occurred on 26th December 2004 and 27th February 2010

Date	Mw	H, km	Earthquake mechanism	Location	Rupture length, km	Rupture width, km
26.XII.2004	9,1	30	Thrust type	3,316°N; 95,854°E	1200-1300	270
27.II.2010	8,8	30	Thrust type	35.89 S; 73.04 W	600-650	100

differences. So, the reasonable explanation is connected with the presented model and due probably to the displaced water volumes. These numbers depends mainly on the average water depth in the areas of bottom displacements and their sizes. The energies released are 1/3 to ¼ and depend on the magnitudes (Milusheva, Ranguelov, 2006). The energy released for both shocks are $3.35x10^{18}$ [J] for the first shock and $1.21x10^{18}$ [J] for the second one.

The geodesy data and displacements of the plates

The use of geodesy data (and especially the GPS data) in the case of the two big earthquakes is rather complicated because of the several reasons: the biggest displacements have been located underwater; the observed displacements on the surface have been located relatively far from the earthquake sources; the used models have different assumptions (all of them trying to fit the observational data) which lead to different results.

To avoid these differences several methods based on geodesy have been suggested to eliminate uncertainties about the Sumatra event: the Scripps scientists with their Indonesian counterparts at the National Coordination Agency for Surveys and Mapping in Cibinong, West Java, measured the shift in position of GPS stations whose locations had been accurately determined prior to the earthquake; the second method, pioneered at the California Institute of Technology, the researchers studied giant coral heads on island reefs. The top surfaces of these corals normally lie right at the water surface, so the presence of corals with tops above or below the water level indicated that the earth's crust rose or fell by that amount during the earthquake.

Finally, the researchers compared satellite images of island lagoons and reefs taken before and after the earthquake: changes in the color of the seawater or reefs indicated a change in the water's depth and hence a rise or fall of the crust at that location (http://track.sfo.jaxa.jp/en/contents/news.html).

The average motions measured prior the great earthquakes have been estimated according the long term measurements. The results about the long term crustal displacements and deformation patterns in South East Asia in average reached 4-5 cm/yr, determined by GPS campaigns conducted since 1994 up to present. They show a rigid plate, moving independently from Eurasia, with deformed boundaries. Residual vectors near the boundaries are usually small (<3 mm/yr) except in north Sumatra where the 6 mm/yr residual pointing indicates "high coupling" with the subduction.

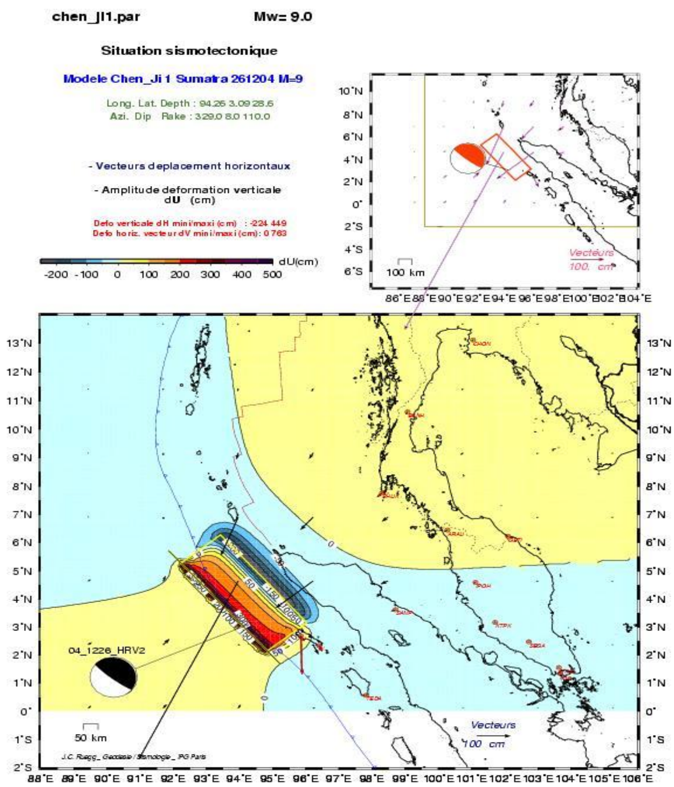

Fig. 6. The model of rupture displacements about great Sumatra earthquake (according http://www.drgeorgepc.com/)

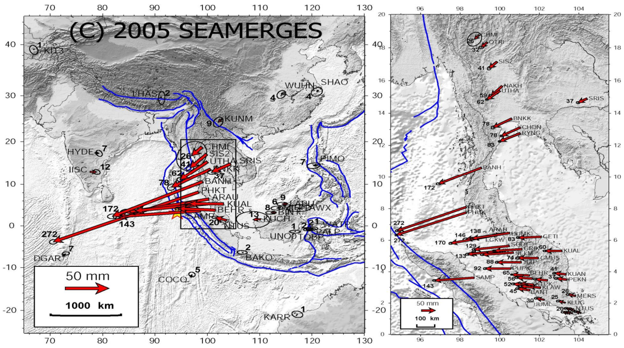

Fig. 7. GPS displacements due to the great Sumatra seismic event

For the Chile earthquake the inverse solution shows again a megathruste seismic event with smaller magnitude

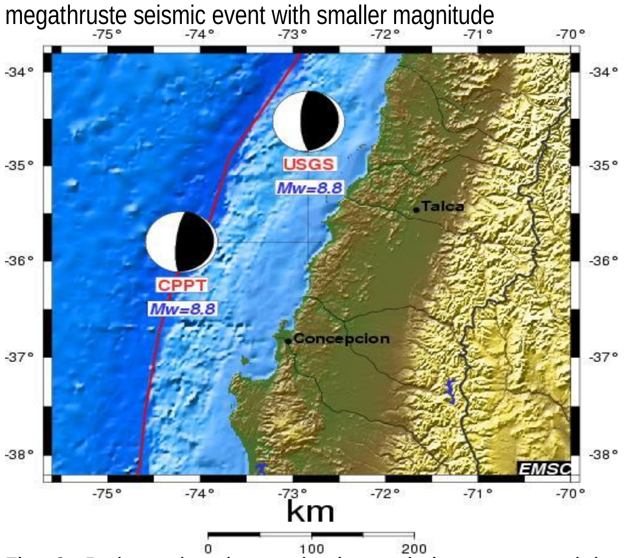

Fig. 8. Both earthquake mechanism solutions presented by USGS and CPPT show again thrust type event

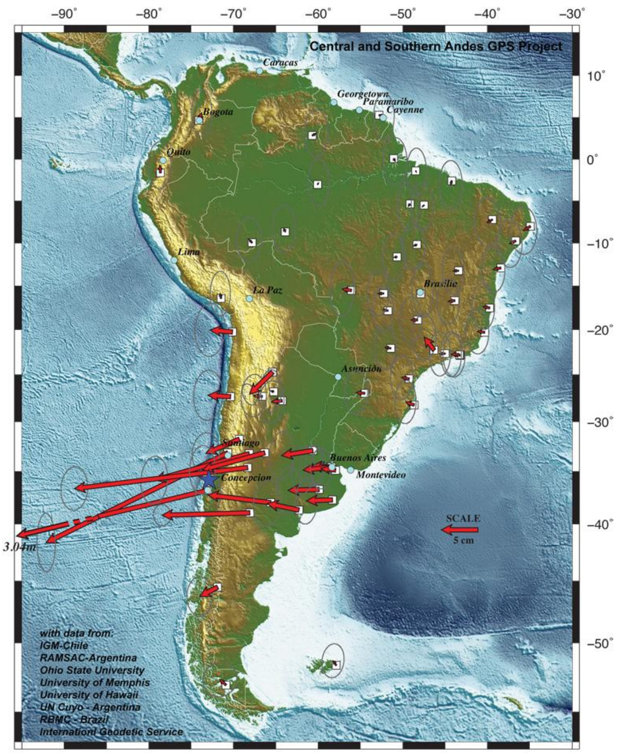

Fig. 9. The GPS displacements of the part of South America continental plate due to the Chilean Mw8.8 seismic event

Conclusions

It is clear that the subduction zones are highly seismic potential arfeas due to the stress accumulation and sudden stress release. This peculiar behavior is the main reason about observed strongest seismic events realized in the subduction zones. The relatively fast movement of the plates, the intrusion of the down plate under the upper one and the stress accumulation and release, are those most important factors due to which the strongest seismic event can occur there. Both investigated strong seismic events confirmed this assessment. The aftershock activity and distribution help a lot to outline the volume of the destructions and stress release.

It is visible and really clear that the geodesy and GPS are the only performed measurements, which can provide reliable and fast information about the sudden plate movements. This data and information helped the solutions of the inverse problem to establish the correct development and space-time history of the seismic process.

The results obtained discover that during the recent years show that the GPS measurements can help to detect the whole (or the part) continental plate displacements due to the very large earthquakes located in subduction zones. After the discovery of the free oscillations of the Earth, the observations of the effects of big parts of the plates' displacements are the second very great result to confirm the plate movements due to the sudden disturbances. The decrease of the measured GPS horizontal displacements (for example clearly visible to the Chile earthquake), shows that it is rather difficult to explain and/or practically unexplainable to consider plates (even in a big scale) like pure elastic bodies which have nonlinear behavior (Ranguelov et al., 2005). The observed attenuation of the displacements observed on far field zones in South America shows that the movements far from the epicentral area are smaller thus proving the nonelastic behavior of the continents – fact not very frequently considered during the large scale models of the Earth crust and geodynamics.

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