Earthquake Related Deformation Cycle: Perspectives from 2004 Sumatra and 2010 Chile Mega-Earthquakes

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Abstract

An earthquake cycle consists of pre-seismic, inter-seismic, co-seismic and post-seismic phases of deformation. Studying these processes using geodetic observations facilitates estimating earthquake recurrence time interval. The advances made in space-borne technologies e.g. Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) have made most profound impact on these measurements and understanding of the processes in earthquake cycle. In the past two decades, high resolution observations before, during and after large earthquakes reaffirmed the basic concept of earthquake cycle. The mega earthquakes: M_w 9.3 Sumatra earthquake on December 26, 2004 and the recent M_w 8.8 Chile earthquake on February 27, 2010 and many other such large earthquakes, prompted lithosphere-scale studies in which space-borne geodetic data are acquired and used to infer the mechanical properties of faults and the rheology of the lower crust and lithospheric mantle. As these parameters essentially control the temporal and spatial distribution of surface strain at all scales, evaluating their characteristics is one of the present day challenges in continental dynamics. This paper focuses on geodetic, geologic and historic studies, as well as laboratory investigations of the earthquake related deformation cycle.

Keywords: Spatio-temporal Elastic Deformation, Four-Phase Earthquake Cycle, Mega Earthquakes, Rheology, Recurrence Interval, Subduction Zones, Sumatra and Chile Events.

Introduction

The idea of the earthquake cycle (seismic cycle) was developed by Harry Fielding Reid[13] to explain his observations of the San Francisco earthquake of 1906. The earthquake related deformation cycle consists of mainly four phases (Fig. 1), namely the pre-seismic (nucleation) phase, the inter-seismic phase (long periods between large earthquakes during which elastic strain accumulation occurs in the broad region), the co-seismic phase (brief period during which the accumulated strain is released during earthquakes) and the post-seismic phase (the period immediately after an earthquake) which exhibits relatively higher rates of deformation wherein the material deforms in response to the sudden coseismic release of strain. Recently, it has been debated whether there exists at all a pre-seismic or nucleation phase that sets in before (time ranging from a year to a decade) the occurrence of a great earthquake. Geodetic evidence for the existence of such a phase does not seem to be conclusive enough. However, it is argued that this period can be recognized as the earthquake preparation period that often comprises earthquake precursors of various kinds[9].

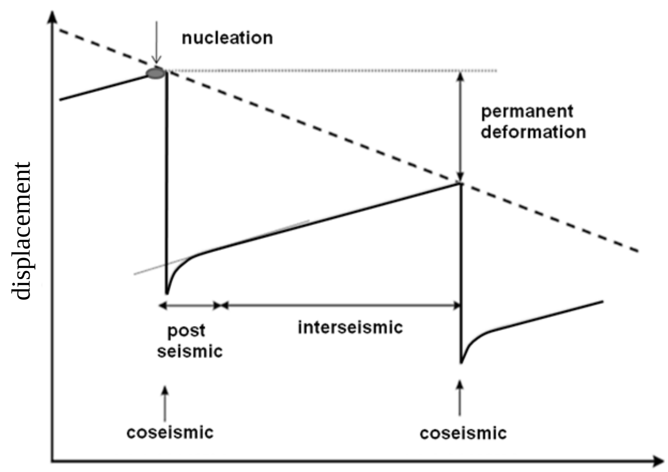

Figure 1: An idealized seismic cycle constituting four distinct phases: pre-seismic, inter-seismic, co-seismic and post-seismic phases.

The concept of seismic cycle, where the stress on a fault repeatedly builds up over a long period of time and rapidly released in a large earthquake, influences studies of both the basic physics of faulting and applied geophysical research aimed at estimating earthquake hazards. This basic hypothesis suggests that large earthquakes might be quasi periodic and that the probability of a particular segment of a fault rupturing twice in quick succession should be low. However, it has been difficult to verify this hypothesis owing to long repeat times of the largest earthquakes on most faults. But, the recent Chile earthquake on February 27, 2010 and the Sumatra earthquake of December 26, 2004 have provided means to evaluate the seismic cycle hypothesis owing to their fast slip rates estimated at about 50 years and 200 years respectively corresponding to their recurrence interval.

It is quite evident that earthquakes are direct manifestations of crustal deformation processes. Figure 2 summarizes the temporal and spatial scales of deformation associated with various geodynamic processes. At present, we have various methods including space-borne technologies, such as GPS and InSAR, to measure the surface crustal deformation thereby enhancing our potential in understanding the earthquake cycle. Figure 3 shows the temporal scales associated with the pre- co- and inter-seismic phases of the earthquake cycle. Figs. 2 and 3 compare the operative temporal and spatial scales accessible through some of the techniques used to measure deformation. Deformation also varies with time, although the only well documented time dependence to date is directly associated with co- and post-seismic phenomena[10]. In seismic zones, the spatial density of points required to explain the sources of crustal deformation is strongly influenced by the thickness of the elastic layer.

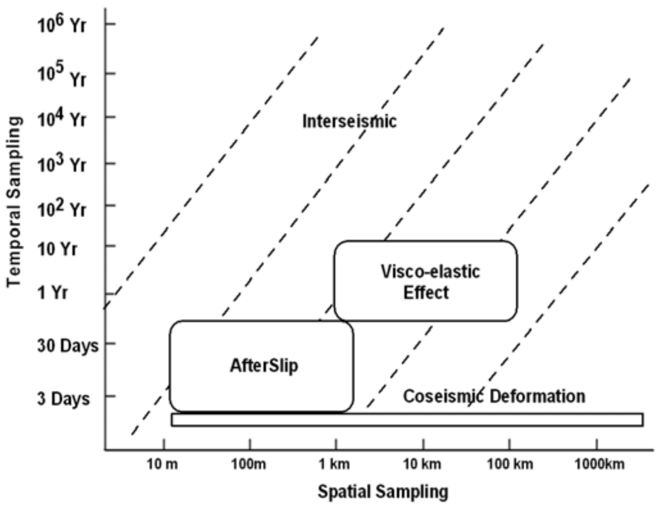

Figure 2: Temporal and spatial scales of earthquake related deformation

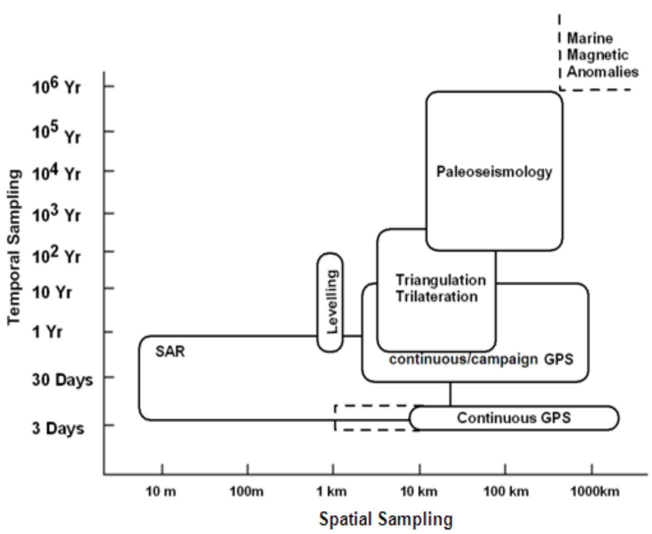

Figure 3: Various techniques of monitoring spatio-temporal earthquake cycle

Observational studies that include comparisons of fault slip rates from geodetic and geologic investigations and modeling studies that utilize a single earth model to account for the full earthquake deformation cycle are considered important. This has prompted us to analyze the scenario in which two great earthquakes occur recently, namely 2004 M_w 9.3 Sumatra earthquake and 2010 M_w 8.8 Chile earthquake.

The Longest Earthquake Cycle vis-à-vis the Shortest

Geologic evidence shows that at least 13 mega earthquakes occurred in the last 6,000 years, spread out between 200 and 800 years in time which gives an average interval of 500 years between them. Records of past great earthquakes at intervals of about 500 years are also found in sheltered inlets and bays along the coast[12]. Radio carbon dating also shows that a set of great seismic events last occurred about 300 years ago with successive great earthquakes 500-600 years apart.

A simplistic procedure to obtain such periodicities is as follows. At a depth interval of 0.5-2 m, there are buried peat layers consisting of vegetation identical to that of the present intertidal marsh surface. The peat layers are interpreted to be former intertidal marsh vegetation that was submerged by abrupt coastal subsidence at the time of past great earthquake. Following each such event, coastal mud accumulated on the drowned marsh, building the surface back to mid-tide level allowing vegetation to be reestablished. Further convincing evidence comes from sand layers that cover the buried marsh surfaces. The sand is interpreted to have been carried in by the great tsunamis that rushed into the subsided coastal region.

As far as the shortest earthquake cycle is concerned, there are some interesting results from California as detailed by Tomes[34]. In this region, in a period of 35 days during the year 1995, 806 earthquakes were reported by United States Geological Survey (USGS). From these data, regular peaks of event occurrence were found at 26 minute intervals. Although, this time is just enough to get the seismic waves to get to the far side of the earth, but not back again and the events could not easily be explained by causes within the earth. If earthquakes have their causative feature entirely within the earth, then the minimum period for a related effect should be 44 minutes. However, if they are caused by factors outside the earth, then it is possible to explain the 26- minute periodicity. If there are causes outside the earth that make the earth deform with dipole terms, then a pair of two opposite points on the earth would be similarly stressed at the same time.

The seismic waves from these would then naturally swap places in 26 minutes leading to a repeat of the same conditions. Tomes[34] further explains that the period of the 26- minute cycle in earthquake repetitions is related to the time for an earthquake wave to travel half way around the world and is therefore a dipole in the whole earth oscillation. The possibility that the earth was being stimulated by gravitational waves of about this period was investigated and experts in gravitation research agree that the gravitational waves of this magnitude are extremely unlikely to exist in our part of the universe.

Construction of Earthquake Cycle using Microfossil Records

Researchers identified key species of microfossils for diagnosing the magnitude of subsidence and developed methods for quantifying the amount of elevation change using a mathematical approach involving appropriate transfer functions. As work continued, researchers found several additional cases of apparent pre-seismic subsidence of the order of 10–30 cm. In the case of March 27, 1964 M_w 9.2 earthquakes in Alaska, the duration of the pre-seismic phase has been found to run though a decade, as determined from the concentrations of Caesium-137. Based on some of these analyses, Shennan et al[30] proposed a four-part deformation cycle, adding this short period of decimeter-scale subsidence before the main event. Further work by Shennan and Hamilton[29] as well as analyses by Hawkes et al[8] which include some new microfossil types, support the four-part cycle for many but not all cases of great earthquakes in Alaska and Cascadia.

More evidence for the past great earthquakes comes from sediment deposits well offshore on the floor of the Cascadia deep sea basin. For example, core samples show turbidite fine-grained mud layers alternating with sandier layers; the coarser layers are interpreted to be formed by submarine landslides triggered by great earthquakes. The intervening mud layers were formed by the slow and continuous rain of finer sediment settling from the ocean. The turbidite chronology is similar to that obtained from the coastal marsh deposits.

An additional clue comes from the ancient records of tsunami related damage on the Japan coast. In contrast with the short record on the Cascadia coast[12], Japan has a long and well documented historical record of damaging tsunamis. The most recent Cascadia subduction zone great earthquake (January 26, 1700; magnitude 8.7 to 9.2) appears to have generated a tsunami that travelled across the Pacific Ocean and did considerable damage on the coast of Japan. The wave heights of 2-3 m in Japan and computed wave dynamics models predicted tsunami wave heights of about 10 m on the Canadian coast. Correcting for the tsunami travel time to Japan and the time zone difference, the source of this great earthquake must have been along the North American coast with an origin time of approximately 9 pm.

Nanyang Technological University in Singapore has long been using coral growth rings to quantify the pattern of slow uplift and subsidence in the Mentawai Islands area. This is the result of stress build-up on the plate interface, which should eventually be released by future large earthquakes in that region.

Simulation of Earthquake Cycle at Subduction Zones

In a brief review, Hirahara[11] explained the simulation of the earthquake cycle in suduciton zone scenario. It is basically divided into two categories which are based on kinematic and quasi-static (or quasi-dyanamic) approaches. In the kinematic approach, the slip evolution along the plate boundaries is considered. This approach is so simple but effective in the computation of surface deformation during an earthquake cycle for an assumed slip along plate boundaries in elastic or viscoelastic media. A simple homogenous elastic half space is assumed in such studies, but slips deficit inversion in viscoelastic media which includes the effect of postseismic deformation lasting for a few decades, has been recently formulated. Inversion studies considering 3-D heterog-eneous viscoelasticity give an accurate estimation of the spatio-temporal slip deficit distribution along the plate boundaries.

In the quasi-static approach, certain generation of earthquake mechanisms (based on laboratory derived friction laws) is considered. This approach is able to successfully simulate several aspects of earthquake cycles in subduction zones. The only drawback is that this approach assumes homogeneous elastic half space, which is always far from truth, particularly in subduction zones. Towards a realistic simulation of earthquakes, we need to develop a special simulation code, which enables handling of a huge amount of meshes or grids using super-parallel computing techniques. A multi-platform simulation, GeoFEM, has been developed by Yagawa et al[40] for solving such solid earth problems.

Rheology and Postseismic Deformation

Bürgmann and Dresen[1] provided a review of approaches to deduce rheology of the lower crust and upper mantle from experimental field geologic and geodetic evidences. Understanding rheology is an essential prerequisite for quantitative study of many geological, geophysical and geodynamical phenomena. Presently, the subject of rheology has become a distinct branch of geodynamics that concerns deformation and flow of matter. Major earthquakes facilitate understanding rheological properties of the earth's crust and mantle and provide insight into processes involved in the earthquake cycle.

Earthquakes cause perturbation in stress distribution in the environing crust such that some places experience a reduction in the tectonic stress while some other places have an increase in the stress. The places of increased stress are more important and it is these regions where aftershocks tend to occur obeying Omori's law[35]. The relaxation of stress takes place at stress perturbed regions and may cause crustal deformation for months to years after a major earthquake.[17-19,26,36] This relaxation manifests as a time dependent mechanical response of the host rocks to the co-seismic stress changes. Thus, analysis of post-seismic deformation provides a good deal of information on rheological properties of the lower crust and upper mantle. There are many possible mechanisms of post-seismic deformation. These mechanisms include afterslip[27,28], viscoelastic relaxation[5], poroelastic rebound[16], hydrothermal deformation, re-equilibration of fluid in a highly fractured stratum, crustal inelasticity[39] and fault zone collapse[27].

An outstanding problem in crustal deformation studies is the role of the lower crust and mantle in the earthquake cycle. The lack of seismicity beneath the upper crust and the behavior of minerals at the temperatures thought to prevail there suggest that both the lower crust and mantle should flow and sustain little permanent stress. As of now, both the strength of such flow and its character as to whether it is broadly distributed or localized are largely unknown. Another pertinent question that arises in this context concerns whether the behaviour of these regions is similar during the inter-seismic period (the long period of stress build-up leading to an earthquake) and the post-seismic period (the few years after a large earthquake).

The Recent Sumatra and Chile Earthquakes

In the last 100 years, there are three discrete periods in which super-sized earthquakes spiked. These are all large subduction zone earthquakes where the ocean floor is pushed under a nearby continent. The three periods referred to herein seem to fit into nearly 20-year discrete blocks of time each, namely 1905-1925, 1950-1968 and 2004 till present. We are thus in the middle of the third one now. In fact, the M_w 8.8 Chilean earthquake on February 27, 2010 is ranked by the USGS as the fifth largest earthquake recorded since the year 1900. The M_w 9.3 earthquake that struck off the coast of northern Sumatra on December 26, 2004 ranks the second largest devastating earthquake in the recorded history of such earthquakes till date. However, both the largest earthquake ever and the third largest earthquake known so far came in the second block of those periods that produced equally deadly earthquakes comprising the M_w 9.5 (Chile, 1960) and M_w 9.2 (Alaska, 1964) events. The 1964 Alaska earthquake struck Prince William Sound area and caused extensive damage in Anchorage.

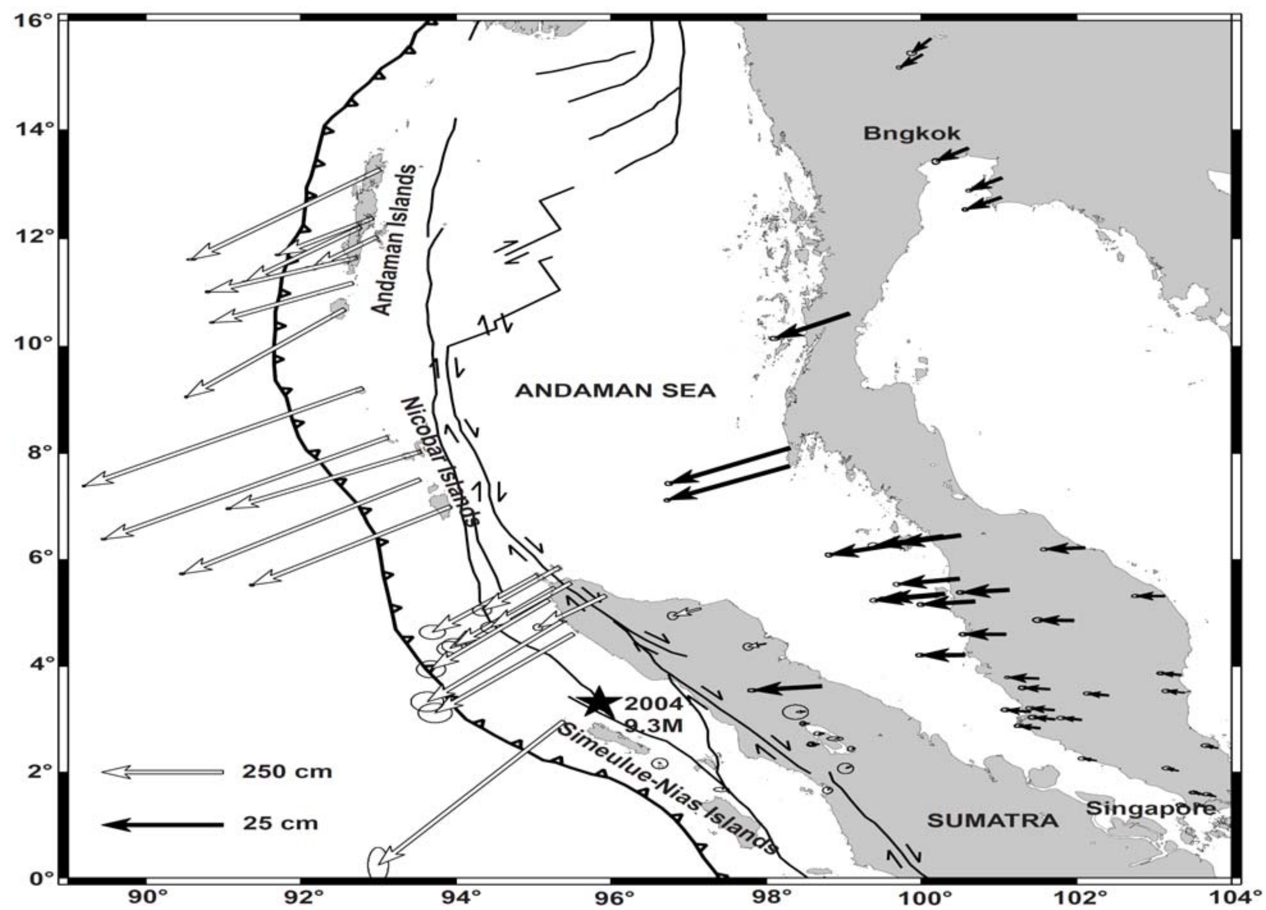

Figure 4: Co-seismic displacements in Sumatra-Andaman region following the December 26, 2004 earthquake shown by arrows whose lengths are proportional to displacements. Star indicates the epicenter location of the earthquake. The pertinence data employed here are pooled from the publications by Vigny et al [37], (horizontal vectors in black), Subraya et al [32] and Gahalaut et al [7] (horizontal vectors in white)

The 2010 Chile earthquake shortened the length of each Earth day by approximately 1.26 microseconds or nearly one millionth of a second. The earthquake may have also shifted the Earth's figure axis by some 3 inches. In comparison, the 2004 Sumatra earthquake shortened the length of an Earth day by 6.8 microseconds, while shifting the planet's axis by 2.32 milliarc seconds, or 2.76 inches. Even though the Chilean earthquake is much smaller than the Sumatran quake, it is predicted to have changed the position of the Earth's figure axis by a bit more for two reasons. First, unlike the 2004 Sumatran earthquake, which was located near the equator, the 2010 Chilean earthquake was located in Earth's mid-latitudes, which makes it more effective in shifting the Earth's figure axis.

The Sumatra earthquake: The Sumatra region falls under a subduction zone where India, Australia and Sunda plates are converging. The Indian plate is subducting underneath the Sunda and Australia plates. This process has repeatedly produced great interplate earthquakes along the intervening trenches with a recurrence time of about a hundred years. At 00:58:50 UT, on December 26, 2004, the M_w 9.3 earthquake in northern Sumatra ruptured the plate interface while the resulting tsunami compounded the devastating effects of the mega earthquake. An analysis of the teleseismic waveforms revealed that the earthquake occurred on a 15° northwest dipping fault plane at about 30 km focal depth. It had a rupture length greater than 1200 km of the plate boundary to the north, more than 100 km wide downdip as determined by high frequency seismic energy radiation[15] and produced an average displacement of about 15 meters on the fault plane. This earthquake, besides causing significant crustal deformation in Indian mainland, was strong enough to cause detectable changes on the earth's rotational parameters, pole shift, length of the day and oblateness[3]. Detailed tectonic features of the affected region are described by Curray[4]. The co-seismic displacements in the Sumatra-Andaman region following the great earthquake are reproduced for illustration in fig.4 on the backdrop of a simplified tectonic map

Gahalaut et al[6] believe that the permanent and campaign mode GPS measurements in the Andaman–Nicobar region would help in constructing the earthquake cycle. Analyses of GPS measurements in the Andaman-Nicobar region by Reddy et al[23,24] and Prajapati and Reddy[20] identified some segments of the earthquake cycle, particularly in the post-seismic phase. The post-seismic getodetic velocities are given in fig. 4. From the limited data sets from Andaman -Nicobar region, Catherine and Gahaluat[2] suggested an earthquake cycle which is compatible with the other earthquake cycles observed at other subduction zones of the world. Prawirodirdjo et al[21] have given details of geodetic observations of an earthquake cycle at the Sumatra subduction zone and the role of inter-seismic strain segmentation. From the studies of Ancient corals that reveal cycles of seismic activity, Quirin[22] comes out with a warning of a potent earthquake in the Sumatra region.

The Chile earthquake: On May 22, 1960 occurred at Valdivia, Chile, the strongest earthquake (M_w 9.5) known so far in the history of earthquakes. Just very recently on February 27, 2010, a massive earthquake (M_w 8.8), centered a few hundred kilometers north of the 1960 earthquake source, revisited the same tectonic block elongated though Central Chile. This megathrust earthquake resulted from the release of mechanical strain in a terrane where the Nazca tectonic plate is being subducted beneath the South American plate. The two plates are converging at a rate of 70 mm per year. The earthquake rupture zone was over 600 km long and 130 km wide. The earthquake was caused by thrust faulting on the interface between the two plates, with the Nazca plate moving down landward below the South American plate. It originated in an offshore zone that was under increased stress caused by the previous (1960) mega earthquake. More than 50 aftershocks of magnitude greater than 5, the largest measuring 6.9, have been recorded since the main event.

The rupture zone of this event is believed to lie between the 1960 event to the south and the 1906 event to the north, offshore of Santiago. According to Ruegg et al[25], at least 10 m of slip deficit had accrued on this segment of the plate boundary since the last great subduction zone earthquake much earlier in 1835. The USGS finite fault model for the February 27, 2010 event seems consistent with this estimate, showing about 450 cm of displacement at the seafloor surface and approaching to be 900 cm near the hypocenter. Figure 5(a) shows the location of the main earthquake of 2010 along with its focal mechanism and the co-seismic displacement field associated with it, based on USGS data. Typical values of measured co-seismic displacements in the all the three components (east-west, north-south and up-down) as a function of time at one station (CONG) are illustrated in figure 5(b).

Results and Discussion

Seismic activity is a manifestation of internal processes at work within the lithosphere. We make use of certain concepts of seismic cycle to facilitate observations of some global scale patterns in seismic energy release over decades. Each mega earthquake represents an extreme critical event of this manifestation. Most of the world's largest earthquakes ($M > 8$) have occurred on subduction zone thrust faults with segmental rupture characteristics governing the repeat interval of those large earthquakes.

Stress and strain evolve as part of the geodynamic process in earthquake cycles. Presently, observed inter-seismic deformation is a snapshot of a changing field. There are fundamental similarities between earthquake cycles of different subduction zones. This is one main reason for choosing to discuss the examples of the Sumatra and Chile earthquakes which represent subduction zone scenarios. Loveless et al[14] provide clues to normal and reverse faulting driven by the subduction zone earthquake cycle in the northern Chilean fore-arc. Further, studying multiple subduction zones presently at different phases of earthquake cycles help us to understand full cycle more comprehensively which will require to distinguish between common (fundamental) processes and site-specific processes. Since the time span of a physical process in any cycle could be very large, we should study several samples in various phases of the complete cycle which requires to study as many subduction zones as practicable which have different stress evolution processes.

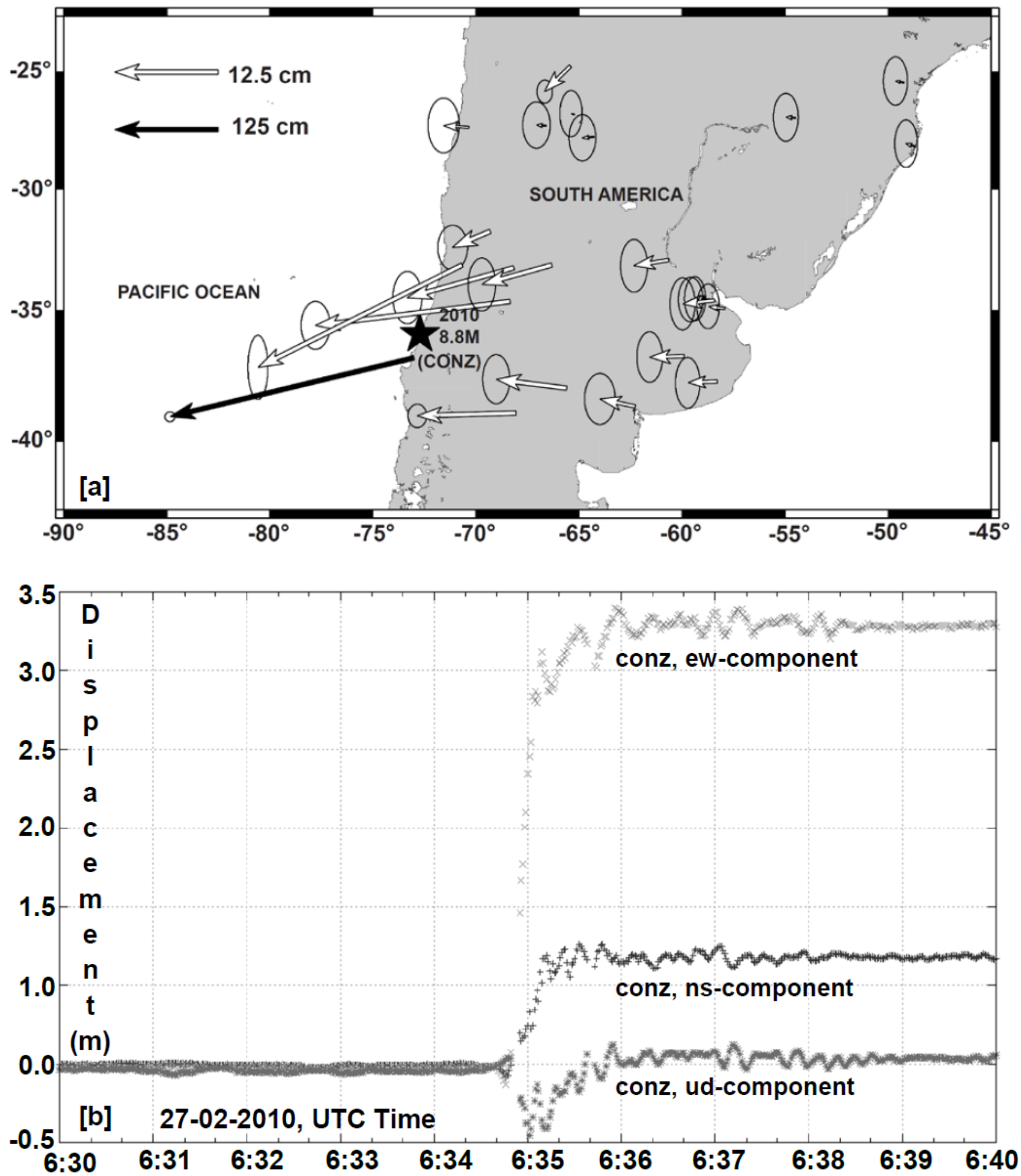

Figure 5: (a) Co-seismic displacement field marked by arrows of different lengths in proportion to displacements associated with the recent M_w 8.8 Maule earthquake in South Central Chile on February 27, 2010. Location of the earthquake can be seen where the black color star is placed. Maximum displacement of 304 cm is observed at GPS site CONZ whose displacement time series in east-west (ew), north-south (ns) and up-down (ud) components are shown in fig. 5 (b). The data sets are from the site http://www.unavco.org

Geodetic and geologic observations from well-studied earthquakes such as the 2004 Sumatra[21] and the 2010 Chile[14], provide a sound basis for exploring the deformation cycle facilitating recurrence time estimation. In ideal circumstances, the time-predictable model requires knowledge of only the seismic slip and time of the last earthquake along with the rate of relative plate motion or fault slip[33]. Owing to short- and long-term post-seismic transients (commonly 20–40 per cent of the coseismic strain drop), the deformation rates are variable and not simply related to the plate motion rate. At strike-slip plate boundaries, however, these complications can sometimes be overcome so that seismic slip and slip rate can be obtained more or less directly. When these favourable circumstances are absent and knowledge of the deformation cycle is incomplete, recurrence estimation accuracy can be improved by empirically correcting for unknown elements of the cycle. Systematic features in the spatial distribution of the transients and permanent deformation near subduction zones help in identifying the regions where these corrections are excessively large and where some of the shortcomings of the empirical approach are most severe.

The 1960 Chile earthquake caused over time large increase in stress on both the northern and southern ends of its rupture plane. This 2010 Chile earthquake picked up where the 1960 rupture ended in the north. This case is similar to the 2004 Sumatra earthquake, which was followed by an indeed large earthquake (M_w 8.7) around Nias on March 28, 2005 on the southern end of the 2004 Sumatra rupture zone. The only difference is that it took 50 years for the northern neighboring section of the 1960 Chile rupture zone to generate another great earthquake in 2010, while it took a much shorter time (only 3 months) for the southern adjacent segment of the Sumatra rupture zone to produce yet another large earthquake in 2005. It would need to look into the seismtectonics in detail to model the recurrent behavior of the rupture zone in the two cases.

The Sumatra subduction zone is the case of a locked fault zone extending into the mantle[31]. The basic process of generation of great earthquake is represented by elastic rebound. When the elastic stress in the vicinity of a locked fault exceeds the sliding strength of the fault, there is abrupt slip and the elastic energy radiates as earthquake waves. The fault eventually relocks and the cycle resumes.

In the Sumatra subduction region, recurrence intervals of earthquakes are not tied to the overall rate of subduction, which ultimately drives the earthquake cycle. Instead, short recurrence intervals seem to correspond to geologic terranes with high topography and potentially weaker material. This inference is supported by the observation that the best-documented cases of repeating earthquakes occur near the junctions of locked and continually slipping fault segments thereby suggesting that the interaction between different rheological regimes, such as plastic flow and brittle deformation, is probably important. Nevertheless, these confounding observations make it difficult to fully understand the spatio-temporal dynamics of earthquakes.

It would have been very helpful if the Sumatra region were intensively monitored in the decade before the massive earthquake struck it in 2004. Some parts of coastal areas along subduction zones have been instrumented with networks of continuous GPS sites in the past 10–15 years. But only few cases in the world have precise and dense enough coverage with geodetic arrays to detect slow earthquakes; measuring vertical motions is even more of a challenge. Nonetheless, those systems that are in place are helping us to understand the fundamental mechanics of subduction zones. Whether this behaviour includes precursory subsidence, remains an open question.

It seems that most of the recent earthquakes in the Sumatra subduction region have been able to relieve seismically the previous centuries of built-up tectonic stress. For instance, an area just south of the 2004 event, where a magnitude 8.7 earthquake occurred in 2005, happens to be the same area which was the site of a major earthquake in 1861 effectively relieving the stresses that had built up since then. This means that it should be a few centuries before another large earthquake in that area recurs. But the same cannot be said of the area further south along the same subduction zone, near the Mentawai Islands consisting of a chain of about 70 islands off the western coasts of Sumatra and Indonesia. This area is known to have been struck by giant earthquakes in the past (M 8.8 event in 1797 and M 9.0 event in 1833). More recently, on September 12, 2007, it experienced two earthquakes just 12 hours apart: first a magnitude 8.4 earthquake and then another of magnitude 7.9 soon after.

Thus, for a comprehensive understanding of the earthquake cycle in a given region, spatio-temporal deformation pattern plays an important role. In this context, Wright[38] reviews some of the remarkable observations of the earthquake cycle already made using radar interferometry and speculate on breakthroughs that are tantalizingly close. In the coming years the Global Navigation Satellite System (GNSS), such as GPS, GLONASS, GELILEO, with the constellation of Earth monitoring satellites supplemented by a dedicated InSAR missions is expected to lead to an immensely improved understanding of the physics of the earthquake cycle, a nearly comprehensive time-varying map of the Earth's strain. In addition, if we are able to integrate these studies with those of the crustal geodynamics employing appropriate geophysical methods and techniques, this would perhaps help to evolve a workable model towards earthquake predictability.

Conclusion

In this paper we focused on some of the important characteristics of the geodynamical processes to understand earthquake related deformation cycle using geodetic, geologic and historic studies, as well as some laboratory based results. The two recent mega earthquakes in particular, viz. the 2004 Sumatra and the 2010 Chile earthquakes provided impetus and necessary data sets for this in-depth study. In accordance with our present understanding, while large earthquakes in active subduction zones have apparently no definite temporal pattern, some moderate to large earthquakes in those regions however, tend to show a curious regularity with regard to spatial pattern.

During the past two decades, substantial data pertaining to deformation cycle have become available from the space-borne technologies, such as GPS and InSAR, in seismically active areas. These data sets provide more complete observations of deformation during all the phases of the earthquake cycle, but are unfortunately restricted to time scales that are too short in comparison to earthquake repeat times. To compensate for this deficiency, we need to look into new geologic approaches by measuring fault offsets, especially advanced dating techniques which are capable of providing more precise estimates of long-term fault slip rates of multiple earthquakes including those of historic and pre-historic origin. Integrating and comparing results from these different approaches will provide further constrains on the mechanics of strain accumulation and release. Geodetic and seismic studies that include comparisons of fault slip rates and seismotectonic modeling to account for the full deformation cycle are of vital importance to closely understand the physical basis of the spatio-temporal patterns of large earthquakes.

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