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A RHEOLOGICAL MODEL OF POST-SEISMIC RESPONSE DUE TO 2004 SUMATRA-ANDAMAN EARTHQUAKE: CONTRIBUTION FROM LOW VISCOSITY LITHOSPHERE

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The Sumatra earthquake on December 26, 2004 provided an excellent opportunity to investigate the post-seismic crustal deformation and thereby understand the rheology of the crust and mantle. Subsequent to this earthquake, we monitored the post-seismic deformation at strategically located five continuous GPS sites in Andaman and Nicobar region. The post-seismic transients are obtained and the viscoelastic modeling has been carried out. Post-seismic flow below a depth of 55–60 km with low viscosity of the order of 10^{19} Pa S can explain observed far field motion. There is also a contribution from upper mantle to post-seismic deformation which follows power law rheology. These results lead us to infer that the Sumatra-Andaman mechanical lithosphere is about at ∼55 km depth.

Keywords: Post-seismic response; rheological model; low viscosity lithosphere.

1. Introduction

"Everything flows and nothing abides; everything gives way and nothing stays fixed". This phrase is quoted by Greek philosopher Heraclitus of Ephesus (536–470 BC). We are familiar with the concept of fluid flow. Solids also flow, but under the suitable conditions of stress and time. The science that pertains to these aspects is called "rheology". More precisely, rheology is the science of deformation and flow of matter. Bürgmann and Dresen [2008] provide a review of approaches to deduce the rheology of the lower crust and upper mantle from experimental, field geologic and geodetic evidences. Understanding the rheology is an essential prerequisite for the quantitative study of many geological, geophysical and geodynamical phenomena. Presently, the subject rheology became distinct branch of geodynamics. 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 have a reduction in stress, and other places have an increase in stress. The places of increased stress are important and it is these regions where aftershocks occurs obeying Omori's law [Utsu, 1961]. The relaxation of stress takes place at stress perturbed regions and may cause crustal deformation for months to years after a major earthquake [Vergnolle *et al.*, 2003; Rydelek and Sacks, 1990; Pollitz, 1992; Pollitz and Sacks, 1992; Pollitz *et al.*, 2000]. 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 information on rheological properties of the lower crust and upper mantle. There are many possible mechanisms of post-seismic deformation. These mechanisms include afterslip [Shen *et al.*, 1994; Savage and Svarc, 1997], viscoelastic relaxation [Deng *et al.*, 1998], poroelastic [Peltzer *et al.*, 1996], hydrothermal deformation [Wyatt *et al.*, 1994], re-equilibration of fluid in a highly fractured stratum [Wyatt *et al.*, 1994], crustal inelasticity [Wyatt *et al.*, 1994] and fault zone collapse [Savage and Svarc, 1997].

Based on rheological constitutive stress-strain equations and laboratory experiments and characteristics of post-seismic transients, three of the above post-seismic mechanisms viz afterslip (via either velocity strengthening frictional slip or linear viscous creep), visco-elastic relaxation, and poro-elastic relaxation (occurs in the upper crust) are most accepted. The major difference between the first two mechanisms is that afterslip is localized while visco-elastic relaxation is a bulk deformation process. Space based geodetic data (e.g. from GPS, VLBI, SAR) provide post-seismic transients (position time series). These transients ought to obey rheological laws and provide information on density, rigidity, viscosity etc. Post-seismic effects have been observed after many large earthquakes [e.g. 1906, M = 8.3, San Francisco earthquake, Kenner and Segall [2000]; Great Alaskan earthquake, Freymueller *et al.* [2000]. Several authors have used transient signals in GPS derived velocities to infer the viscosity of the crust and/or mantle in various tectonic environments [e.g. Pollitz *et al.*, 2001]. The Sumatra-Andaman earthquake on December 26, 2004 provided yet an opportunity to study co- and post-seismic phenomena and to infer the rheological properties of the lithosphere in the subduction environment of Andaman and Nicobar region.

2. The Post-Seismic Transients

To delineate the post-seismic deformation, we require the cumulative surface deformation (time series of the position coordinates) for few years. Following the 2004 Sumatra-Andaman earthquake, an array of GPS sites (as shown in Fig. 1, located in the vicinity of $\sim$1000 km from the epicenter) has been established in Andaman and Nicobar region. We used both Leica and Trimble receivers with chockring antennas and at each site the data have been collected with fixed sampling interval of 30 sec and tracking satellites above 15° elevations. This GPS network facilitated obtaining the surface post-seismic transients extending at the rates more than 30 cm/yr in the

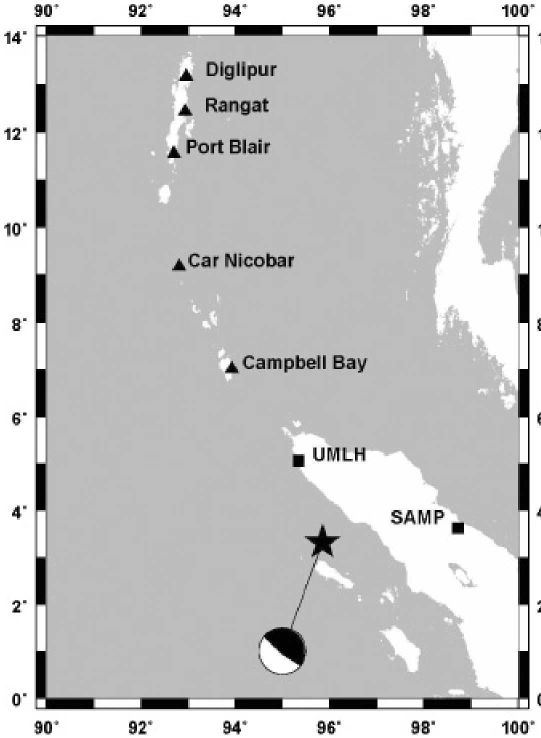

Fig. 1. Network of GPS sites considered for the study. The triangles indicate GPS sites in Andaman and Nicobar region which are set up following the Sumatra earthquake. The star locating the December 26, 2004 Sumatra earthquake.

near field during 2005–2006. These post-seismic transients are expected to follow the above mentioned relaxation mechanisms involving the crust and mantle.

We considered two years of horizontal post-seismic deformation following the Sumatra-Andaman earthquake. Using these two years data, at first, we removed the annual and semiannual signal from GPS derived position time series $u(t)$ (as given below) and obtained post-seismic transients. The main contribution for seasonal variation comes from pole tide effects, ocean tide loading, atmospheric loading etc. An anatomy of seasonal variations in GPS-site position time series is explained by Dong *et al.* [2002]. The average annual and semiannual components for east, north and up components (in mm) are of the order of 2.0, 1.8, 4.6 and 0.8, 0.4, 1.6 respectively [Boschi *et al.*, 2005]. These transients follow the rheological laws and can be expressed as either logarithmic decay which represents afterslip [Marone *et al.*, 1991] and/or exponential decay [Savage and Prescott, 1978]. The position time series [Dong *et al.*, 2002; Kreemer *et al.*, 2006] can be written as:

$$u(t) = vt + X\sin(2\pi + \phi_i) + Y\sin(4\pi + \phi_2) + c + a\left\langle \begin{matrix} \ln(1 + t/\tau_{\log}) \\ 1 - e^{t/\tau_{\exp}} \end{matrix} \right.$$

where:

$u(t) =$ displacement as function of time t
$v =$ linear velocity
$c =$ (co-seismic) offset
$X =$ amplitude of annual cycle
$\Phi_1 =$ phase offset of annual cycle
$Y =$ amplitude of semiannual cycle
$\Phi_2 =$ phase offset of semiannual cycle
$a =$ amplitude of post-seismic decay
$\tau_{\log} =$ decay time corresponding to logarithmic decay
$\tau_{\exp} =$ decay time corresponding to exponential decay

Time series of horizontal components (EW and NS) of position coordinate show (a) a linear term representing strain accumulation due to inter-seismic and plate motions, (b) an annual and semiannual periodic terms representing seasonal affects, (c) a logarithmic/exponential term representing post-seismic deformation. This approach has been used only as a curve-fitting convenience to remove seasonal effect and estimate displacement uncertainties. In Andaman region, as shown in Fig. 2, it is observed that all the transients are best expressed by exponential function indicating that viscoelastic relaxation is dominant.

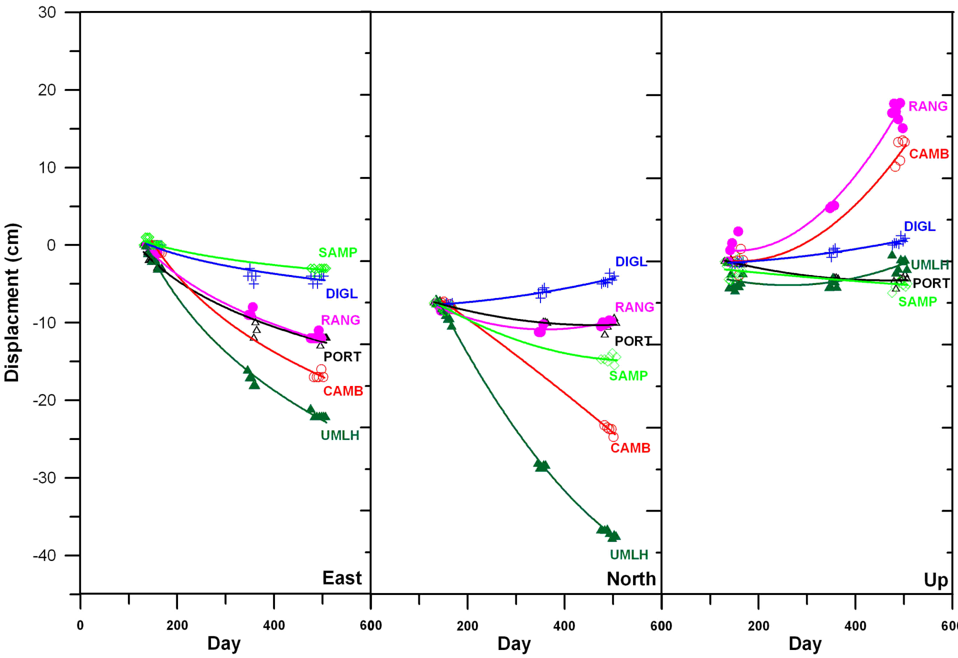

Fig. 2. Post-seismic transients in east, north and up components at six sites. Five sites (except UMLH) are located in Andaman and Nicobar region as shown in Fig. 1. The solid lines are exponential fits to the post-seismic transients.

The main reason for the viscoelastic relaxation phenomenon is the inability of the hot lower crust and/or upper mantle to sustain imparted co-seismic stress changes. On the timescales of an earthquake rupture, the entire lithosphere responds to the earthquake in an elastic manner. However, co-seismic stress cannot be sustained in these hot, deeper region and they relax viscously in the years to decades following the earthquake. This includes transfer of stress both laterally and upward to the shallow seismogenic crust, causing observables post-seismic deformation.

3. Conceptualizing the Post-Seismic Model

Viscoelastic relaxation modeling is computed on the basis of normal mode relaxation models with Maxwell viscoelastic rheology [Li and Rice 1987; Hager *et al.* 1999]. This rheology consists of viscoelastic material which behaves elastic for short time scales (1–10^4 sec) and as viscous fluid for long time scales (10^{11} to 10^{17} sec). This rheology is shown in Fig. 3 using spring (elastic element) and dash pot (viscous element). The total strain is $\varepsilon = \varepsilon_e + \varepsilon_f$ i.e. the sum of elastic and fluid strain. Where $\varepsilon_e = \sigma/E$ and $\mathrm{d}\varepsilon_f/dt = \sigma/2\mu$. The latter term corresponds to Newtonian fluid (with viscosity μ) under a deviatory normal stress σ. Thus, the fundamental rheological equation for Maxwell viscoelastic material relating strain, strain rate, stress and viscosity is $d\varepsilon/dt = (\sigma/2\mu) + d\sigma/Edt$. This yields stress relaxation expression $\sigma = \sigma_0 \exp(-Et/2\mu)$. The viscoelastic relaxation time $\tau = 2\mu/E$ (i.e. $1/e$ of initial stress) is very useful parameter in conceiving the temporal post-seismic deformation by viscoelastic relaxation mechanism.

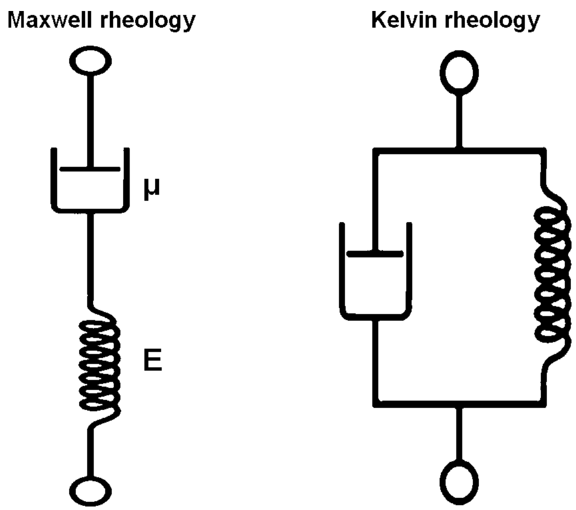

Fig. 3. Elastic (spring) and viscous (dash pot) elements for Maxwell (left) and Kelvin rheology (right).

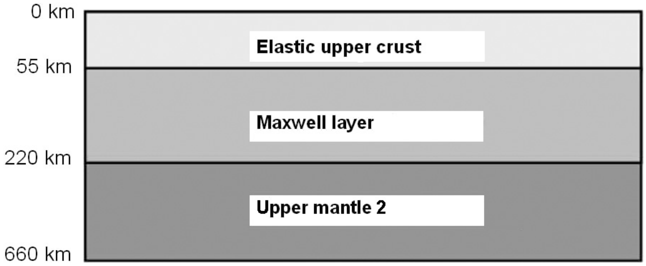

Fig. 4. A layered viscoelastic model considered for simulating the post-seismic response. Viscosity, shear and bulk modulus of each layer are given in Table 1.

Table 1. Rheological parameter for the layered model shown in Fig. 4.

Layer	Depth KM	Viscosity Pas	Bulk Modulus Pa	Shear Modulus Pa
UC	0–55	$(0.1\text{E}+12)\times 10^{18}$	5×10^{10}	3×10^{10}
LC	55–220	$(3-5)\times 10^{18}-10^{19}$	13×10^{10}	7×10^{10}
LCB	220–660	$2-3\times 10^{21}-10^{22}$	20×10^{10}	10×10^{10}

4. Viscoelastic Relaxation Modeling

To investigate the contribution of post-seismic deformation due to viscoelastic relaxation, we adopted semi-analytical approach, considering stratified earth model and co-seismic fault plane solution. The layered earth model is shown in Fig. 4 and its parameter (shear modulus, bulk modulus, density) are based on PREM [Dziewonski and Anderson, 1981] which shows three major discontinuities at depth of 55 km (UC), 220 km (UM1) and 660 km (UM2) (lower crust/upper mantle). We kept constant viscosity between discontinuities. The modeling is carried out confined to normal mode theory at high spatial resolution. In normal mode approach, the spheriodal and toroidal components of the equilibrium are expanded in spherical harmonics [Phinney and Burridge, 1973]. For earthquake sources, both spheriodal and toroidal components of the normal mode solution are propagated through multilayered, self gravitating, viscoelastic earth model [Pollitz *et al.*, 2006].

As the Sumatra-Andaman earthquake was one of the most important seismic events a detailed description of the fault system has been obtained from seismic waveform inversion [Ammon *et al.*, 2005]. An rms analysis to constrain the rheology of upper mantle; a full search in the viscosity space makes it possible to constrain the mantle viscosity to values of the order of $\sim 10^{19}$ Pa s.

To obtain the predicted velocity and displacement we preferred the fault model (the parameter are given in Table 2) derived from 142 horizontal GPS displacement vectors and 30 vertical GPS displacement vector from Banerjee *et al.* [2006]. Banerjee *et al.* [2006] argue that, without northern 650 km of Andaman segment slip model, the fit is significantly worse than model including the Andaman segment. The 2004 Sumatra-Andaman slip model provide the source model for calculating

Table 2. The fault model parameters used for simulating the post-seismic velocity for the layer viscoelastic model given in Fig. 4. Fault locations are from south (upper row) to north (lower row) as shown in Fig. 5.

Max Depth of Fault (km)	Min Depth of Fault (km)	Length (km)	Dip (deg)	Strike (deg)	Rake (deg)	Slip (cm)
60.00	35.00	160	30	360	110	400
60.00	35.00	180	30	300	100	2000
35.00	2.00	180	16	40	100	800
35.00	2.00	180	15	32	120	600
35.00	2.00	160	10	20	115	600

the post-seismic displacements at selected sites for a given rheological layered earth model given in Fig. 4.

Since temporal variation of gravity reflect the mass redistribution and its influence that can be estimated only after several years [Pollitz, 1997], we examined only the non-gravitational aspect of post-seismic relaxation of Sumatra-Andaman earthquake. The comparison of modeled estimates and observed velocity vectors are shown in Fig. 5, for each year. It is observed that, near and far field velocity are well correlated with assumed model parameters.

5. Discussion and Conclusions

A major problem in understanding the post-seismic response of the lithosphere to an earthquake is that of uniqueness of the model. Savage *et al.* [1978] shows a post-seismic deformation due to viscoelastic relaxation of an asthenosphere half space can be reproduce by a properly chosen model. Several authors [e.g. Shen *et al.*, 1994; Savage and Svarc, 1997] explained the post-seismic response using only afterslip mechanism. While some authors [e.g. Deng *et al.*, 1998; Pollitz *et al.*, 2000; Freed and Burgmann, 2004] explained the response with viscoelastic relaxation. A combination of viscoelastic relaxation and afterslip mechanisms with various tradeoffs also have been attempted. In our study we did not consider afterslip and poroelastic rebound, rather we preferred considering a wider range of viscoelastic rheologies. Mostly poroelastic contribution is considered to fit the near field data and it is operative within the few weeks after the earthquake. On the other hand, afterslip is more dominated in Sumatra-Andaman region during first six months of the post-seismic period. In our study, we did not consider afterslip and poroelastic rebound (by avoiding first six months of data) rather we preferred considering viscoelastic relaxation mechanism with a wide range of viscoelastic rheologies which fit the observed data well.

Our model results implicate several conclusions such as (i) no single mechanism can explain the post-seismic deformation, (ii) significant post-seismic flow below a depth of 55 km with low viscosity 3×10^{18}–4.5×10^{19} Pa s can explain observed far field motion, (iii) there is also a contribution from upper mantle to post-seismic deformation which follows power law rheology. These conclusions lead us to infer a Sumatra-Andaman mechanical lithosphere that is about at ~55 km depth. With the

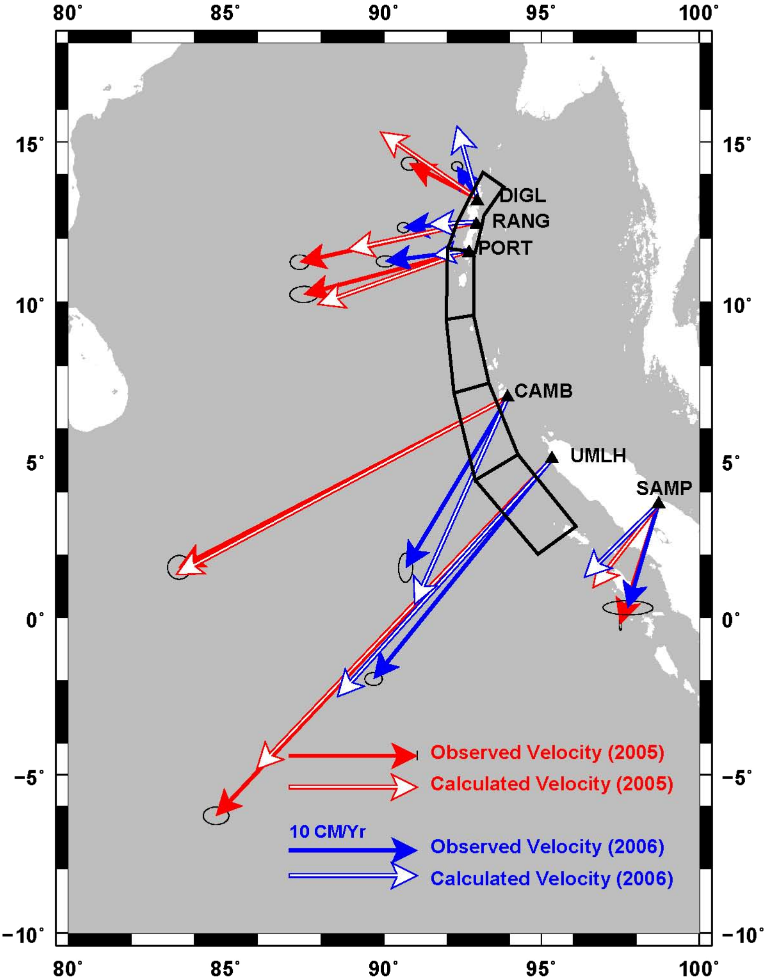

Fig. 5. Comparison of post-seismic GPS observed and calculated surface velocity associated with 2004 Sumatra-Andaman earthquake. Assumed Co-seismic fault plane also shown in the figure.

average viscosity of 4.0×10^{19} Pa s and a shear modulus 7 GPa, the relaxation time ∼18 years. Our results span a relatively short i.e. two year's post-seismic period, and not indicative of longer term processes. It is interesting to observe that our mechanical lithospheres best simulating the observed response is similar to other subduction zones where properties are based on long term observations. Our inferred low viscosity is based on two years data is almost identical to the 3×10^{18}–4.5×10^{19} Pa s suggested by Freed *et al.* [2006] for 2002 Denali, Alaska earthquake. The relatively low inferred viscosity of the mantle in these regions may be due to short time span of the observation considered in the combination with a stress dependent rheology, where initially high co-seismic stress leads to low viscosities [Freed and Bürgmann, 2004].

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