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Postseismic deformation following the 1999 Chi-Chi earthquake, Taiwan: Implication for lower-crust rheology

Baptiste Rousset,1,2 Sylvain Barbot,1,3 Jean-Philippe Avouac,1 and Ya-Ju Hsu4

Received 26 June 2012; revised 18 October 2012; accepted 24 October 2012; published 15 December 2012.

[1] On 1999 September 21, the Mw 7.6 Chi-Chi earthquake ruptured a segment of the Chelungpu Fault, a frontal thrust fault of the Western Foothills of Taiwan. The stress perturbation induced by the rupture triggered a transient deformation across the island, which was well recorded by a wide network of continuously operating GPS stations. The analysis of more than ten years of these data reveals a heterogeneous pattern of postseismic displacements, with relaxation times varying by a factor of more than ten, and large cumulative displacements at great distances, in particular along the Longitudinal Valley in eastern Taiwan, where relaxation times are also longer. We show that while afterslip is the dominant relaxation process in the epicentral area, viscoelastic relaxation is needed to explain the pattern and time evolution of displacements at the larger scale.

We model the spatiotemporal behavior of the transient deformation as the result of afterslip on the décollement that extends downdip of the Chelungpu thrust, and viscoelastic flow in the lower crust and in the mid-crust below the Central Range. We construct a model of deformation driven by coseismic stress change where afterslip and viscoelastic flow are fully coupled. The model is compatible with the shorter relaxation times observed in the near field, which are due to continued fault slip, and the longer characteristic relaxation times and the reversed polarity of vertical displacements observed east of the Central Range. Our preferred model shows a viscosity of $0.5 \times 10^{19}$ Pa s at lower-crustal depths and $5 \times 10^{17}$ Pa s in the mid-crust below the Central Range, between 10 and 30 km depth. The low-viscosity zone at mid-crustal depth below the Central Range coincides with a region of low seismicity where rapid advection of heat due to surface erosion coupled with underplating maintain high temperatures, estimated to be between 300°C and 600°C from the modeling of thermo-chronology and surface heat flow data.


1. Introduction

[2] It has long been recognized that large earthquakes are commonly followed by transient "postseismic" deformation and various mechanisms have been proposed involving either fault zone deformation or distributed viscoelastic relaxation of the medium affected by co-seismic stress change, with eventual coupling between fluid flow and deformation [e.g., Benioff, 1951; Brown et al., 1977; Nur and Mavko, 1974; Tse and Rice, 1986; Wang, 2007; Bürgmann and Dresen, 2008; Segall, 2010]. The relative importance of these mechanisms is not well constrained because they can give rise to similar surface displacements [Savage, 1990; Thatcher and England, 1998; Hearn, 2003; Bruhat et al., 2011; Ryder et al., 2011] and is likely to vary from place to place. Constraints on crustal and mantle rocks rheology from laboratory experiments [Brace and Kohlstedt, 1980; Kohlstedt et al., 1995; Hirth et al., 2001; Tullis, 2002; Hirth and Kohlstedt, 2003] warrant the occurrence of distributed viscoelastic flow in the lower crust and upper mantle. Similarly, friction laws derived from laboratory experiment predict that transient postseismic slip, usually referred to as afterslip, should occur on faults obeying a rate-strengthening friction law as is expected at depths where temperature exceeds about 250°C or near the surface within poorly consolidated sediments [Marone et al., 1991; Blanpied et al., 1991; Tse and Rice, 1986]. It has turned out repeatedly difficult to discriminate the relative importance of these two mechanisms.

[3] In addition to the inherent trade-offs between the signatures of afterslip and viscoelastic flow, the overprinting of near-fault phenomena such as fault zone collapse [Savage et al., 1994; Massonnet et al., 1996; Pollitz et al., 1998;
2. Overview of Geological Setting and Chi-Chi Earthquake Characteristics

[7] The Taiwan orogen has resulted from the collision between the continental margin of the South China and the Luzon Arc on the Philippines Sea Plate [Suppe, 1981; Angelier, 1986; Angelier et al., 2001; Malavieille et al., 2002]. The convergence between the South China and the Philippine Sea Plate occurs at a rate of about 90 mm/y [Sella et al., 2002] and the collision initiated ~6.5 Ma ago. Taiwan is composed from west to east of the Coastal Plain, the Western Foothills, the Central Range (CR), the Longitudinal Valley (LV) and the Coastal Range. The Longitudinal Valley is thought to coincide with the suture zone. The CR is composed from west to east of the Coastal Plain, the Western Foothills, the Central Range (CR), the Longitudinal Valley (LV) and the Coastal Range. We reconcile the various observations using a stress-driven model of postseismic deformation, including a full account of the coupling between afterslip and viscoelastic flow. The method allows us to gauge the relative contribution of afterslip and viscoelastic deformation in a consistent manner, and with limited simplifying assumptions.

[6] In Section 2, we give an overview of the geological setting and deep structure of Taiwan. In Section 3, we describe the postseismic transient and its unique features, and how it is isolated from other spurious effects in the GPS time series. In Section 4, we test the potential of single deformation mechanisms to explain alone the geodetic observations. In Section 5, we determine a class of physical models of coupled afterslip and viscoelastic flow which explains most aspects of the postseismic transient. We finally discuss the implications for the lower-crust rheology.
The Western Foothills is a non-metamorphic fold-and-thrust belt composed of foreland and marginal deposits accreted to the growing orogenic wedge. Shortening within the mountain belt is accommodated by slip on thrust faults and related fault-bend folding above a basal décollement [Suppe, 1981; Yue et al., 2005]. The crustal thickening of the hinterland suggests that the CR has grown as a result of both frontal accretion and underplating of material scrapped off from the underthrusting South China continental crust [e.g., Wu et al., 1997; Mouthereau et al., 2002; Simoes et al., 2007; Beyssac et al., 2007]. The September 21 1999, Mw 7.6 Chi-Chi earthquake ruptured the Chelungpu Fault within the Western Foothills fold-and-thrust belt [Ma et al., 1999; Lee and Ma, 2000; Yu et al., 2001; Johnson et al., 2001; Lee et al., 2002; Dominguez et al., 2003; Chang et al., 2007].

Figure 2. Decomposition of GPS time series (black) for station SUN1, close to the epicenter, and far-field station FLNM, into the interseismic (blue), coseismic (magenta), postseismic (green) and seasonal variations (not plotted) contributions. While the amplitude of the horizontal signal is almost the same for both stations, the far-field transient is ~7 times longer than the near-field one. The step at SUN1 in 2006 corresponds to the effect of a Mw 6 earthquake. Positions relative to ITRF00.

To guide our analysis of postseismic deformation we evaluate the coseismic stress change associated with the 1999 Chi-Chi earthquake (Figure 3). The computation shows significant stress changes (>0.1 MPa) across most of Taiwan. Such a change is significant because the ambient tectonic stresses are small in the 15–30 depth range, less than 10 MPa typically according to the paleopiezometry study of Kidder et al. [2012]. At 15 km depth, the deviatoric co-seismic stress change is maximum around the rupture, tapers from 0.8 MPa in the middle of the Central Range to 0.2 MPa in eastern Taiwan. The northern and southern areas are less affected. The large stress perturbation extending across the Central Range illustrates where the postseismic deformation may have been triggered by the Chi-Chi earthquake. A cross section of the stress perturbation reveals that the deviatoric stress change is significant at mid-crustal depth below the CR but tapers rapidly down to insignificant values at depth below
the Moho. The contribution to postseismic deformation of the sub-crustal lithosphere is therefore probably negligible.

3. Geodetic Postseismic Transient Deformation

[9] Taiwan is covered by a dense network of continuously recording GPS stations and a wealth of campaign mode data are also available [Chang et al., 2003; Yu et al., 2001; Hsu et al., 2009c]. In this study we use the time series provided by the Academia Sinica, Taipei, available online at http://gps.earth.sinica.edu.tw. We analyze the raw displacement time series in the ITRF reference frame to identify the transient deformation that occurred following the 1999 Chi-Chi earthquake. To do so, it is necessary to single out and remove the contribution of steady interseismic deformation, seasonal variations, coseismic offsets, and other factors that affect the station position time series. Since the 1999 Chi-Chi event, many other earthquakes have occurred throughout the island, including the 2003 Mw 6.8 Chengkung, the 2006 Mw 7.0 Pingtung, and the 2006 Mw 6.1 Taitung earthquakes.
better explained with short relaxation times (the order of six years or more (Figure 2). For all stations, we
in the LV, are best explained with a longer relaxation time, of
example at station SUN1, while other, such as station FLNM
seasonal variations, the
and
C
where
C
xt
[51x0]t
[51x70]t
[51x81]t
[51x92]t

Figure 4. Quality of fit with relaxation times for near-field
station SUN1, and far-field station FLNM. The solid lines cor-
respond to horizontal, and the dashed ones to vertical compo-
ent. A similar analysis is performed on all stations to
respond to horizontal, and the dashed ones to vertical compo-
tion of the time series, we identify when static offsets occur.
In practice, postseismic transients are invoked only for the
Chelungpu Fault or viscoelastic deformation of the CR. Fur-
ther to the south, GPS stations show convergence across the
Western Foothills, which can be explained by transient aseis-
ic creep on the Chukou Thrust, the south extension of the
Chelungpu Fault. Independently to their direction of horizon-
tal motion, these stations experience subsidence. To the north
of the rupture, the relaxation time are largely variable and the
GPS stations in general extrude away from the Chi-Chi rup-
ture. A striking feature in Figure 3 is the large cumulative
displacements observed in eastern Taiwan, compared to, say,
in the Coastal Plain and the Western Foothills at the same
latitude. The stations in eastern Taiwan also consistently show
subsidence and relatively long characteristic relaxation times
(~7 years on average) ranging from 5 up to 10 years or more.
Assuming velocities that decay exponentially, the transient is
63% complete after a period corresponding to one relaxation
time; after the equivalent of five relaxation times, the transient is
more than 99% complete. The longer relaxation times in eastern
Taiwan, quite prominent in the decade-long time series, explain
why such large amplitude of cumulative displacement of the
eastern coastal stations were not detected in previous studies
why such large amplitude of cumulative displacement of the
eastern coastal stations were not detected in previous studies
among the various mechanisms.

where
C
1
is a constant offset, \( C_2 \) is the secular velocity, \( C_3 \)
and \( C_4 \) are related to the amplitude and phase of the annual
seasonal variations, the \( D_i \) are coseismic and other spurious
offsets occurring at time \( t_i \), the \( E_i \) are the maximum amplitu-
de of the postseismic transients starting at time \( t_i \), and \( H(t) \)
is the Heaviside function (step function). By visual inspec-
tion of the time series, we identify when static offsets occur.
In practice, postseismic transients are invoked only for the
2003 Chengkung earthquake, to the south east, and for the
Chi-Chi earthquake. For each time series individually, we
identify the best-fitting relaxation time \( T_i \) in a range between
0.1 and 10 years (Figure 4).

Some stations, particularly in the near-field, are clearly
better explained with short relaxation times (\( T \approx 2 \) yr), for
example at station SUN1, while other, such as station FLNM
in the LV, are best explained with a longer relaxation time,
of the order of six years or more (Figure 2). For all stations, we
perform an independent check of the validity of our decom-
position, and verify that the inferred secular velocity is con-
sistent with the results from earlier campaign GPS and leveling
surveys [Hsu et al., 2009c; Ching et al., 2011], for the hori-
zontal and vertical components, respectively. The GPS cam-
paign data are relative to the GPS station Paisha, Penghu,
located in the Chinese margin, and the leveling data are rela-
tive to the Keelung Harbor tide gauge in northern Taiwan. We
discard the stations that, once placed in similar reference
frames, do not show a consistent interseismic velocity with the
campaign data. This approach is conservative and is meant to
avoid contamination of poorly constrained interseismic signal
in the inferred postseismic displacements. Our analysis results
in about 40 estimations of postseismic transient amplitudes
and relaxation times distributed all over the island.

The cumulative postseismic displacements over ten
years after the Chi-Chi earthquake (Figure 1) reveal a well
organized and complex spatial pattern of deformation. The
near-field stations within the CR, east of the Chi-Chi rupture,
show large westward displacements up to 15 cm with relaxa-
tion time ranging from 1.2 to 2.5 years. This signal might be
consistent with either slip on the down-dip continuation of the
Chelungpu Fault or viscoelastic deformation of the CR. Fur-
ther to the south, GPS stations show convergence across the
Western Foothills, which can be explained by transient aseis-
ic creep on the Chukou Thrust, the south extension of the
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time; after the equivalent of five relaxation times, the transient is
more than 99% complete. The longer relaxation times in eastern
Taiwan, quite prominent in the decade-long time series, explain
why such large amplitude of cumulative displacement of the
eastern coastal stations were not detected in previous studies
that use much shorter periods of observation. For example, at
the station FLNM, the horizontal transient motion will be 99% 
completed about 32 years after the main shock, whereas at near-
field station SUN1 the transient is already largely completed.

Mechanisms of Deformation

In this section we discuss the potential respective contribu-
tion of poroelastic rebound, afterslip and viscoelastic relaxation
to the observed postseismic deformation. We discuss qualita-
tively the merits and shortcoming of these various mechanisms
and compare quantitatively the models predictions with the
observed transient displacements. The root mean squares of
the misfits obtained for the best models are listed in Table 1.

4.1. Poroelastic Rebound

The strain field resulting from sudden fault slip pro-
duces gradients in pore fluid pressure in the crust that are
relaxed by fluid flow [e.g., Peltzer et al., 1996; Jonsson et al., 2003]. Following the Chi-Chi earthquake, widespread coseismic change in pore water pressure next to the Chelungpu Fault were evidenced by conspicuous water level changes in wells, ranging from 1 to 10 m [Chia et al., 2001; Wang et al., 2001]. During poroelastic rebound, the porous rocks evolve from the undrained conditions, when the pore fluid has just been pressurized, to the drained conditions, when the pore pressure gradients have been fully relaxed [Biot, 1956; Rudnicki, 1985; Detournay and Cheng, 1993; Wang, 2000; Barbot and Fialko, 2010b]. The drained condition is associated with reduced effective Poisson’s ratio, the shear modulus being unaffected. Experimental studies provide us with approximative values of undrained \( \nu_u \) and drained \( \nu_d \) Poisson’s ratios for a given rock type [Kumpel, 1991]. In Western Foothills of Taiwan, the Cholan and Toukoshan formations consist dominantly of shales, sandstones and conglomerates [Ho, 1988]. An upper bound of the influence of poroelastic rebound might be estimated by considering a large difference between drained and undrained Poisson’s ratio of \( \nu_d = 0.31 \) and \( \nu_u = 0.12 \) which would apply to highly porous sandstone [Rice and Cleary, 1976]. We gauge the maximum contribution of a poroelastic rebound by computing the difference between the result of the coseismic model in undrained and drained conditions [e.g., Peltzer et al., 1996]. Our calculation shows that poroelastic rebound should have caused uplift east of the Chelungpu Fault, and subsidence west of it, which is inconsistent with observations. The maximum displacement predicted from poroelastic deformation is \( \sim 10 \) mm, which represents less than 10% of the observed amplitude in the near field. Consequently, even if poroelastic rebound may have played a role, it is not a dominant process in the postseismic relaxation following the Chi-Chi earthquake.

### 4.2. Afterslip

[14] Postseismic deformation is often attributed to continued, largely aseismic slip in the vicinity of the coseismic rupture [Bucknam et al., 1978; Bürgmann et al., 2002; Freed, 2007; Perfettini and Avouac, 2007; Hsu et al., 2006; Chlieh et al., 2007; Barbot et al., 2008, 2009; Perfettini et al., 2010; Barbot et al., 2012]. This so-called afterslip has been the dominant driving mechanism of deformation during the first few years following the Chi-Chi earthquake [Hsu et al., 2002; Perfettini and Avouac, 2004; Hsu et al., 2007, 2009a]. We reassess the role of afterslip to explain the longer GPS displacement time series across Taiwan. We assume that afterslip can happen on the Chelungpu Fault (Figure 5, Model A), which we describe by two fault planes similar, for example, to the ones used by Hsu et al. [2002].

### Table 1. Sum of Square of Residuals for Stress-Driven Afterslip (A), 3-D Linear Viscoelastic (C) and Coupled Mechanisms (D1 and D2) Models for Horizontal, Vertical and All Components of Deformation*

<table>
<thead>
<tr>
<th>Residuals ( (\times 10^5 \text{ m}^2 \text{ yr}^{-2}) )</th>
<th>Horizontal</th>
<th>Vertical</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A2</td>
<td>2.93</td>
<td>1.51</td>
<td>4.58</td>
</tr>
<tr>
<td>Model C</td>
<td>2.38</td>
<td>1.91</td>
<td>4.48</td>
</tr>
<tr>
<td>Model D1</td>
<td>2.69</td>
<td>1.73</td>
<td>4.42</td>
</tr>
<tr>
<td>Model D2</td>
<td>2.77</td>
<td>1.57</td>
<td>4.42</td>
</tr>
</tbody>
</table>

*These values take into account all stations and the full postseismic time series.

### Figure 5. Schematic models of postseismic relaxation considered in this study. Model A: afterslip on the Chelungpu Fault. The parameters involved are the length of the décollement \( L \), a reference slip rate \( V_0 \) and effective frictional parameters of the fault \( (a - b)\sigma \). Model B: vertically stratified viscoelastic flow in the lower crust, with viscosity \( \eta_1 \) and depth of brittle-ductile transition \( H \). Model C: viscoelastic flow with a low-viscosity block below the Central Range. The block is described by its thickness \( T \), top depth \( h \), and viscosity \( \eta_2 \). The extension of that block in the normal direction of the section is shown in maps of (Figure 11). Model D: coupled afterslip and viscoelastic flow.
The top fault consists in a 20 km-wide ramp dipping 30° east, abutting to a bottom décollement dipping 5° east (Figure 6).

### 4.2.1. Kinematic Afterslip Inversion

We first derive a purely kinematic model of afterslip. To do so, we determine the distribution of slip on the Chelungpu Fault that best reproduces the pattern of surface displacement. We use the formulation of Okada [1992] to compute the Green’s functions between fault slip and surface displacements and optimize the best-fitting afterslip distribution using least squares. The method is similar to the one described by Harris and Segall [1987] or Du et al. [1992]. To limit trade-offs among the various model parameters, a positivity constraint is applied (thrust ±90°). The Laplacian of the slip distribution is minimized so as to force smooth variations of slip between neighboring patches. This model assumes that afterslip is the only mechanism affecting the surface displacements and deformation due to other factors, such as viscous flow or poroelastic rebound, if present would bias the results.

The resulting best-fitting model can explain the amplitude of GPS displacement in the near field and some stations in the far-field, close to Hualien (Figure 7). The large displacements in eastern Taiwan require quite large amounts of afterslip on the décollement abutting the Chelungpu Fault at depth, with a band of maximum slip of ~2.5 m near the eastern edge of the model (Figure 6). Overall the far-field displacements are poorly explained by this model. A similar inversion using cumulative displacements 15 months after the main shock concentrates afterslip close to the epicenter, on the western part of the décollement, with a maximum slip of ~0.7 m [Hsu et al., 2007]. It would require the afterslip response to augment while the co-seismic stress change decreases away from the main shock, something that a dynamic model would not easily be able to reproduce.

### 4.2.2. Stress-Driven Afterslip

We continue the exploration of the role of afterslip by considering stress-driven models of fault creep. The advantage of such a model over a purely kinematic model is that the number of free parameters is reduced and that non-physical solutions, for example with afterslip larger than the slip required to relax co-seismic stress change, are not allowed [e.g., Perfettini and Avouac, 2007]. We use the approach described by Barbot and Fialko [2010a, 2010b], and the corresponding program Relax available at http://www.geodynamics.org, to compute the time-dependent response of rate-strengthening friction faults to the coseismic stress perturbation. Following Johnson et al. [2006] and Barbot et al. [2009], we assume that afterslip is controlled by the rate-strengthening friction law

\[
V = 2V_0\sinh\left(\frac{\Delta\tau}{(a-b)\bar{\sigma}}\right),
\]

a steady state simplification of the rate-and-state friction law [Marone et al., 1991; Dieterich, 1992], where \(V_0\) is a reference slip rate that affects the timescale of the afterslip transient, \(\Delta\tau\) is the fault shear stress perturbation, \((a-b)\) is a frictional parameter and \(\bar{\sigma}\) is the effective normal stress. We use the same fault geometry as used in the kinematic inversion.

By exploring frictional parameters \(a\) and \(b\), we produce a forward model of the afterslip evolution that reproduces the azimuth and amplitude of postseismic displacements in the near field reasonably well (Figure 8). The model does not produce significant deformation to the northern and southern parts of the island, due to the limited extent of the source. Our modeling confirms the results found by others [Hsu et al., 2002; Loevenbruck et al., 2004; Hsu et al., 2007, 2009a], that afterslip can explain the surface deformation in the area of the Chelungpu Fault, even eleven years after the main shock. However, we have not been able to produce stress-driven models of afterslip that can explain near-field and far-field displacements simultaneously, nor the large contrasting relaxation times.

### 4.2.3. Afterslip on Surrounding Faults

Around the Chukou Fault, the south extension of the Chelungpu Fault into the younger, less mature latitudes of the Taiwan collision, a noticeable postseismic motion stands out...
in the GPS times series. Stations CHNL, KULN, S092, GAIS, S012, S106 and TSHO are moving westward, with an amplitude of ~40 mm and a short relaxation time of ~2 years, whereas stations S103, PKGM, S011, CK01 and HOKN, on the footwall of the Chukou Fault, seem not moving (Figure 1). We run a kinematic inversion using only these stations and a fault following the surface trace of the Chukou Fault. The model explains well the horizontal motion of these stations and a fault following the surface trace of the Chukou Fault. The model discretization is illustrated by the small squares. The vertical motion is shown by the background colors for the model and by colored circles for the data.

Figure 7. Surface displacements predicted by a kinematic model of afterslip. The fault discretization is illustrated by the small squares. The vertical motion is shown by the background colors for the model and by colored circles for the data.

that allows slip on Chelungpu and the LVF cannot explain the large LVF displacements with slip consistent with the oblique left-lateral thrust motion of the LVF. In particular, thrusting on the LVF cannot reconcile the westward motion and subsidence of the hanging wall.

[21] The stress-driven model and kinematic inversions taken together indicate that afterslip is a possible source of the near-field deformation compatible with the stress changes produced by the rupture, but that another source of deformation is required below the Central Range to explain in particular the large displacements, the subsidence, and long recurrence times in eastern Taiwan.

4.3. Viscoelastic Relaxation

[22] We consider the potential of viscoelastic flow to explain the Chi-Chi postseismic relaxation, with a particular emphasis on the far field, which cannot be explained by afterslip models. The viscosity of crustal and mantle rocks is a nonlinear function of lithology, temperature, grain size, fluid pressure, confining pressure and stress [e.g., Kohlstedt et al., 1995, and references therein]. We adopt here a linearized rheology

$$\dot{\varepsilon} = \frac{\Delta \tau}{\eta}$$

where $\dot{\varepsilon}$ is the viscous strain rate, $\Delta \tau$ is the stress change and $\eta$ is the effective viscosity, that is deemed appropriate for the prevailing physical conditions and the short period of observation. We use the program Relax to explore the signature of viscoelastic flow driven by the Chi-Chi coseismic stress change.

4.3.1. Case of a Stratified Lithosphere

[23] We first explore the response of a vertically stratified viscoelastic medium. We assume a simple model with an elastic plate overlying a viscoelastic half-space (Figure 5, Model B). The model is parameterized with the elastic plate thickness $H$, and the lower-crust viscosity $\eta_1$. After exploring a range of values on these two parameters, we find that a thin elastic plate of thickness $H=10$ km and a lower-crust viscosity of $\eta_1 = 10^{18}$ Pa s can explain the amplitude of horizontal motion in eastern Taiwan (Figure 9). This model, however, produces large horizontal and vertical displacements in the near field, some uplift in eastern Taiwan, all of which are inconsistent with observations. Our sensitivity tests indicate that the rheology of the upper mantle does not affect the surface deformation much, as found earlier by other investigators [Hsu et al., 2002; Sheu and Shieh, 2004; Chan and Stein, 2009]. Viscoelastic models predict the northward motion of the northern GPS stations as is observed in this area, but stratified viscoelastic models share an unresolvable tradeoff between near-field and far-field stations, where fitting the eastern Taiwan stations give rise to too large displacements in the near field and in the Taipei area.

4.3.2. Case of a Laterally Varying Lithospheric Rheology

[24] Motivated by the high temperatures and low seismicity found in the CR, we now consider the possibility of a three-dimensional effective viscosity structure where viscoelastic flow is allowed in the CR at mid-crustal depths. To test this hypothesis, we augment the stratified model with a low-viscosity zone (LVZ) of viscosity $\eta_2$ beneath the CR,
east of the Lishan Fault (Figure 5c), where temperatures at mid-crustal depths exceed about 300°C according to the thermal structure of Simoes et al. [2007] (Figure 3). The extent of the LVZ follows approximately the Vp and Vp/Vs velocity anomaly of the CR [Kim et al., 2005; Wu et al., 2007] and the domain of overall low seismicity (Figure 10). We allow flow all the way east to the Longitudinal Valley, but because of the proximity to the Chi-Chi earthquake, the western side of the LVZ exhibits the most viscous strain. The three-dimensional setup is characterized by the lower-crust and mid-crust viscosities, $h_1$ and $h_2$, respectively, and the LVZ brittle-ductile transition depth $h$ and thickness $T$ (Figure 5c, Model C). We explore a wide range of parameters until the model explains the near-field and far-field horizontal displacements simultaneously (Figure 11). A striking feature of the three-dimensional model is the prediction of a long stretch of subsidence, east of the Central Range. In this model, the surface deformation in eastern Taiwan is controlled by the width and viscosity of the LVZ. The best model is obtained with $H = 20$ km, $h = 10$ km, $h_1 = 10^{18}$ Pa s and $h_2 = 5.10^{17}$ Pa s. Because the LVZ terminates in regions of low stress change, the forward models are not sensitive to the length of the LVZ. Contrarily to the case of a vertically stratified lithosphere, the three-dimensional model reconciles near- and far-field horizontal amplitudes and the polarity of vertical displacements almost everywhere on the island. However, the linear viscoelastic model predicts uniformly long relaxations times, between 5 and 10 yr, which cannot explain the rapid relaxation of near-field stations. Despite the merits of the laterally varying viscoelastic model, it cannot reproduce satisfactorily some important and robust features of the postseismic relaxation and a more complex model is needed to reconcile the various available observations.

5. Fully Coupled Afterslip and Viscoelastic Relaxation

[25] The analysis of the scenarios involving only a single mechanism reveals that a combination of afterslip and viscoelastic flow is needed to explain the complex pattern and temporal evolution of surface displacements that occur in the decade following the Chi-Chi earthquake. We consider model D in Figure 5 where afterslip occurs on the down-dip continuation of the Chelungpu Fault and viscous strain occurs in the lower crust and mid crust below the CR. The synchronous evolution of afterslip and viscoelastic flow complicates the analysis because viscoelastic parameters affect the velocity of afterslip and the advancement of fault
slip reloads the viscoelastic regions. As we investigate the relative contribution of viscoelastic flow and afterslip by trial and errors, we based this exploration on a few following considerations: 1) the friction properties on the Chelungpu Fault impact less the final amplitude of near-field stations than their relaxation time, the latter being smaller than the total duration of observations; 2) both the length of the Chelungpu Fault and thickness of the LVZ affect the amplitude of horizontal displacements in the near- and far fields; 3) the width and viscosity of the LVZ can reconcile the vertical sense of motion and the amplitude of horizontal far-field displacements.

Figure 9. Surface displacements at GPS stations and for a stress-driven model of vertically stratified viscoelastic flow. The viscoelastic model predicts the escape northward displacements of the GPS stations in northern Taiwan, but there is a tradeoff between fitting the amplitude of displacements in eastern Taiwan and in the near field.

We explored the characteristics of the model needed to explain the main features of the observed postseismic deformation, in particular the contrast between the near- and far-field records. Satisfying results were obtained with models involving afterslip on a 20 km-wide décollement down-dip of the Chelungpu fault, a LVZ width lower than 40 km, a brittle-ductile transition depth of \( H = 30 \text{ km} \) in the Western Foothills and \( h = 15 \text{ km} \) in the CR, and a mid-crustal viscosity of \( \eta_2 = 5 \times 10^{17} \text{ Pa s} \) in the CR (Figure 12). Figure 12 presents the predictions of two models that differ only by the viscosity of the lower crust, with \( \eta_1 = 5 \times 10^{18} \text{ Pa s} \) (Figure 12a) and \( \eta_1 = 10^{19} \text{ Pa s} \) (Figure 12b). Both these models explain a number of observations: the contrasted amplitudes of horizontal displacement in the near- and far fields, the subsidence of eastern Taiwan and coastal areas near Taipei, Taitung and Tainan; the northward displacements of the northern stations, near Taipei; the complex pattern of uplift and subsidence in the near field; and the variability of relaxation times between the Western Foothills and the LV stations (Figure 13). In addition to a better qualitative behavior, the predictions of the coupled model and the GPS time series compare better than other, simpler, models.
(Table 1). On the one hand, model D1, with $\eta_1 = 5 \times 10^{18}$ Pa s, predicts larger strain in the lower crust beneath the Western Foothills but the incorrect polarity of vertical displacements for stations SUN1 and S167; on the other hand, model D2, with $\eta_1 = 1 \times 10^{19}$ Pa s, predicts the correct polarity of vertical displacements for these stations, but over-predicts the subsidence of eastern Taiwan. These results indicate that a small variation in viscosity in the Western Foothills can greatly affect the pattern of surface uplift and subsidence and suggest that even more lateral variations of viscosity may be required to explain subtle features of the vertical displacements than presently considered. It is possible that the slope of the Moho - from 30 km depth in the Western Foothills to 55 km depth below the Central Range [Kim et al., 2005] introduces other lateral variations of viscosity that are not captured by our model.

6. Discussion

[27] Inference of subterranean structure from geodesy alone is often non unique. However, incorporation of other constraints from thermo-kinematic models, seismicity, stratigraphic topography or tomography can help us identifying models of the Earth’s lithosphere that are more realistic. The formulation of self-consistent mechanical models of deformation tuned to observations, such as presented here, can lead to a better representation and understanding of the deformation mechanisms involved in postseismic deformation. Close to the epicenter where co-seismic stress change was the strongest, the large displacements and rapid relaxation are consistent with relaxation being dominated by rate-strengthening frictional sliding on the Chelungpu Fault and its down-dip continuation as shown in previous studies [Hsu et al., 2002; Loevenbruck et al., 2004; Hsu et al., 2007, 2009a]. This mechanism alone fails to explain the large displacements and long relaxation time observed in eastern Taiwan (Figure 14), as well as the subsidence and northward displacements observed in northern Taiwan. These features require deeper and larger sources of deformation with a slower relaxation time.

[28] We show that a combination of afterslip, viscous flow at mid-crustal depth beneath the Central Range and viscous
flow of the lower crust explains many features of the observations (Figure 14 and Table 1). We infer a lower-crust viscosity of $\eta_c = 0.5 - 1 \times 10^{19}$ Pa s and a mid-crust viscosity of $5 \times 10^{17}$ Pa s starting at 10 km depth below the Central Range. The depth to the low viscosity zone is consistent with paleo-piezometric and thermometric data from rock exhumed in the Central Range, which show that the brittle-ductile transition lies at depth of about 8–10 km [Kidder et al., 2012], also quantitatively consistent with a ductile flow law established for quartzo-feldspathic rocks [e.g., Hirth et al., 2001].

The low viscosity of the mid crust below the Central Range inferred in this study is probably the result of both locally high temperatures and higher stress level sustained by the rapid convergence and erosion rates, amplified by the non-linearity of the intrinsic flow law. Kidder et al. [2012] estimate the ambient deviatoric stresses in the mid-crust below the Central Range to about 10 MPa. The stress change due to the Chi-Chi earthquake, although less than 10% of this value, seems to have produced a increase in strain rates of at least a

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Figure 12. Surface displacements at GPS stations and for two models of coupled afterslip and viscoelastic flow that can explain a wide range of observations. (left) Model D1, with lower-crustal viscosity $\eta_c = 5 \times 10^{18}$ Pa s. (right) Model D2, with $\eta_c = 10^{19}$ Pa s. A cross section of the cumulative amplitude of viscous strain is plotted along profile A-A’. The pattern of vertical displacements is very sensitive to the viscous property of the lower crust.
factor of 4. Such an increase is consistent with a non linear law with an exponent of the order of 3.

[28] The postseismic deformation following the 1999 Chi-Chi earthquake illuminated a low-viscosity zone below the Central Range that is consistent with independent constraints from thermal modeling, seismology and rocks laboratory experiments. The higher viscosity of the lower crust could be either due to the non-linearity of the flow law, as the reasoning above comparing the co-seismic and ambient deviatoric stresses suggests, or to a compositional difference between a quartzo-feldspathic upper crust and more mafic lower crust. Comparison of the viscosities inferred from this study with laboratory derived flow laws, which have a non-linear dependency of strain rate with stress, is not straightforward as the strain rates involved in long term geological deformation must be on average one order of magnitude lower than those at play in the early postseismic period. Assuming an exponent of \( n = 3 \) for the stress-dependence of the viscosity, the long-term, average, effective viscosity should be about three orders of magnitude higher than during the first ten years of the Chi-Chi postseismic transient. Even more sophisticated models consistent with the stress evolution before, during, and after the Chi-Chi earthquake may be needed to test the importance and the effect of non-linear viscous rheologies. Furthermore, some investigation is needed to check whether our inferred low-viscosity below the Central Range is compatible with the long-term support of the topography.

7. Conclusions

[30] The postseismic deformation following the 1999 Chi-Chi earthquake exhibits a complex behavior in time and space. The transient can be explained by rapid and localized deformation driven by afterslip on the Chelungpu Fault and the abutting décollement, accompanied and followed by a slower, distributed, deformation in the lower crust. Viscoelastic flow starts at an average depth of 30 km west of the Central Range, with a deep lower-crust viscosity of \( \eta_{lc} = 0.5 \times 10^{19} \) Pa s, which is consistent with the bottom depth of seismicity in central Taiwan. Ductile deformation is much shallower in the Central Range, and extends up to 10 km depth with a reduced viscosity of \( 5 \times 10^{17} \) Pa s. This zone is coincident with an aseismic domain of low seismic velocity, low Vp/Vs ratio, and higher temperatures. The low viscosity in the Central Range can be the combined result of a high thermal gradient and the presence of crustal fluids, as evidence from high geothermal activity and large surface heat

Figure 13. Comparison between the observed effective relaxation times and the ones predicted from our fully coupled model of afterslip and viscoelastic flow. The short relaxation times in the near field and the longer ones in eastern Taiwan are well explained. At other places of smaller amplitude deformation, the spatial variability of relaxation time is also reproduced.
flow. Our study confirms the strong correlation among various mechanical properties of the lithosphere constrained from seismological, petrological and geodetic data and opens the way to developing more realistic descriptions of the lithosphere stress evolution that reconcile various independent geophysical observations.

[31] Acknowledgments. This project was supported by the Gordon and Betty Moore Foundation through the Tectonics Observatory. We would like to thank reviewers Greg Houseman and Andrea Donnellan for their constructive criticism, which we found very helpful in improving the manuscript. We thank the GPS LAB of the Academia Sinica, Taipei for providing us with GPS time series and Jian-Cheng Lee for leading a rewarding field trip in Taiwan. This is Tectonic Observatory contribution 194.

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Figure 14. Merits of the afterslip, viscoelastic and coupled, models to explain the near- and far-field GPS time series. Afterslip-only models (dashed profile) can explain the short relaxation time and amplitude of near-field displacements at station SUN1, but poorly reproduce the far-field displacement at station FLNM. Viscoelastic flow models (black profile) can explain the far-field displacement well, but not the near field. Models of afterslip coupled with 3-D viscoelastic flow (blue curves) offer a better overall fit to the GPS time series across Taiwan with a lower-crust viscosity in the range 0.5–1 × 10^19 Pa s.


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