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# Determining Source Model and Aftershocks of 2006 Yogyakarta Earthquake, Indonesia using Coulomb Stress Change

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**Abstract.** On 26 May 2006 at 22:53:59 UTC, an earthquake with moment magnitude of 6.4 occurred in Yogyakarta, Indonesia. The source of the event is still debatable. Some believe the event was caused by the reactivation of the Opak Fault which has a left-lateral type movement. Previous studies indicated there are two possibilities to explain the mechanism of the Yogyakarta earthquake. First is based on the focal mechanism from NIED (National Research Institute for Earth Science and Disaster) Japan which indicated that the event occurred in an oblique reverse slip. This model states that the complex Opak fault is a flower structure (strike-slip) type. Second is based on NEIC (National Earthquake Information Center) US which indicated that the event was caused by a pure strike-slip fault (active Opak fault). The May 26<sup>th</sup> earthquake triggered many aftershock events around the old Opak fault. The majority of aftershock events on 3-6 June 2006 were located around 5 km east of Opak fault. It has a trendline of N45°E and lies parallel with the Opak fault. We use Coulomb Stress change to determine which type of source model fit better the aftershocks pattern. The target fault for Coulomb Stress analysis is a left lateral pure strike slip with an orientation of N45°E/90°SE.

## 1. Introduction

An earthquake on 26 May 2006 at 22:53:59 UTC with magnitude of 6.4  $M_w$  shook Yogyakarta region, Indonesia. The epicenter was located inland at a depth of 10 km. Many experts suggested that the earthquake was caused by the movement of Opak Fault. Opak Fault is located along Opak River, east of Yogyakarta and serves as a boundary between Gunung Kidul high and Yogyakarta graben [1].

The source mechanism of Yogyakarta event is still debatable. Mainly caused by the lack of subsurface data in and around Opak Fault. There are two source models of the event based on Natawidjaja and Daryono [2]. The first model indicates that the mainshock was caused by an oblique reverse fault movement and Opak Fault is a strike slip fault with positive flower structure forms [3]. The second model assumes the New Opak Fault moved in a strike-slip movement. This triggered the movement from the Old Opak Fault which produced aftershocks in the east of the new fault.

In this study, we attempt to model the two versions of source models based on Natawidjaja and Daryono (2016) [2] using Coulomb stress change. After that, we compare the two models of Coulomb



stress change to determine which source models is the most compatible. The model will be deemed compatible if the stress distribution conforms to the aftershocks pattern and earthquake damage area.

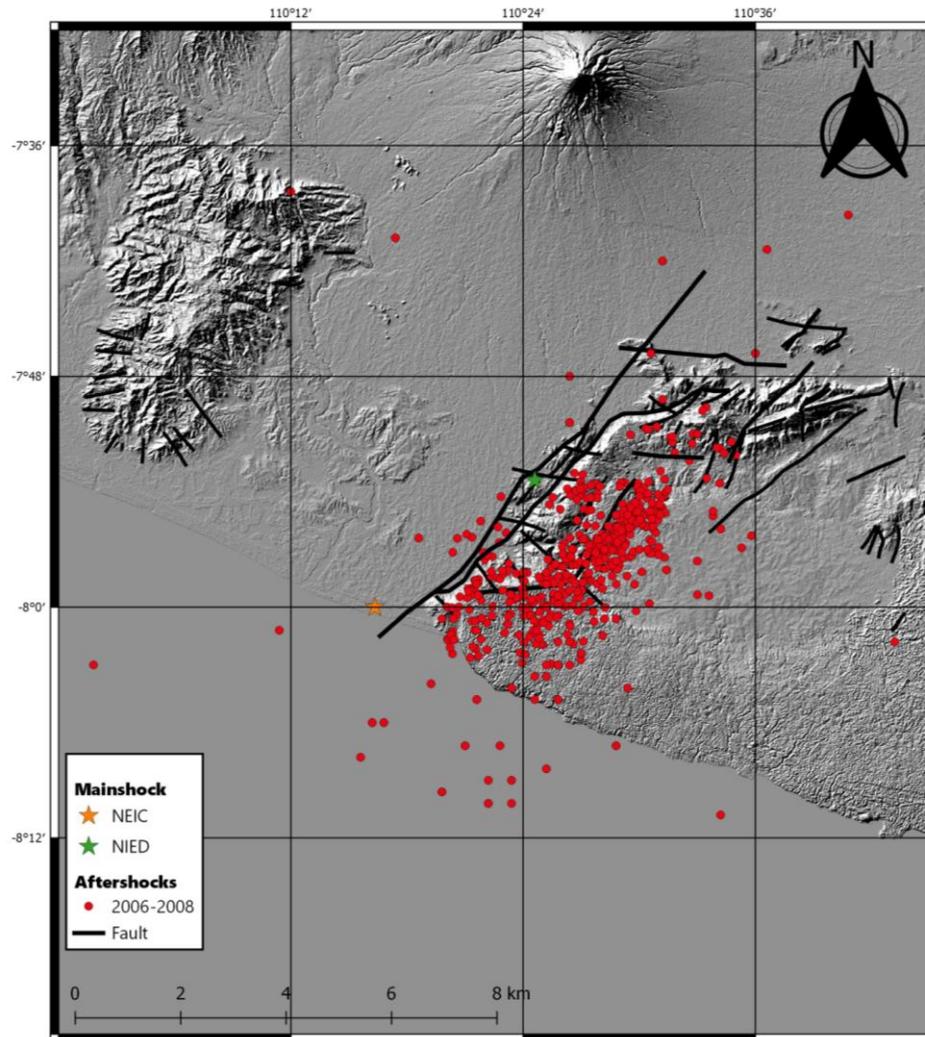


Figure 1. Map view of epicenter and aftershock of Yogyakarta Earthquake 2006.

## 2. Source Model of Yogyakarta Earthquake 2006

According to Natawidjaja and Daryono [2] there are two possibilities of the source models of 2006 Yogyakarta earthquake (Figure 2). These models were obtained from geological and seismological survey in the area. The geological data is according to the tectonic rupture investigation and topography observation. Whilst the seismological condition is based on focal mechanism and aftershocks data.

In the first model, the source is caused by the Active Opak Fault which is a reverse fault. The fault plane dip is  $45^{\circ}$ - $50^{\circ}$  to the east. In depth of 8-10 km, the fault plane become vertical ( $90^{\circ}$ ) and the slip changes to strike-slip. Fault with configuration described above is known as a positive flower structure. The interpreted fault form is indicated by a lineation of the aftershocks. This model is supported by focal mechanism data from NIED (National Research Institute for Earth Science and Disaster) which show an oblique reverse slip. Topographic data around Opak Fault shows that eastern part of Opak Fault rises over the western part.

Second model of 2006 earthquake assumes that slip is generated by New Opak Fault which has a vertical dip. This fault has a left lateral strike-slip movement. Focal mechanism data from NEIC

(National Earthquake Information Center) US supports this model. The model also explains that aftershocks located east of this New Opak Fault is caused by the reactivation of the Old Opak Fault.

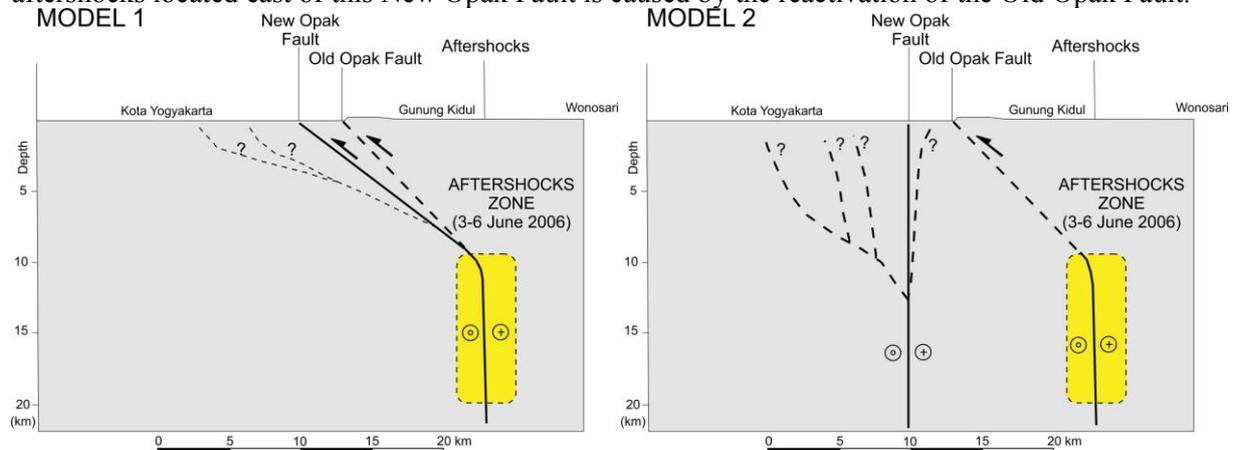


Figure 2. Illustration of source model of Yogyakarta Earthquake 2006. (left) Model 1 and (right) Model 2. (modified from Natawidjaja and Daryono, [2]).

### 3. Coulomb Stress Modelling

Coulomb stress change is used to determine stress change following a mainshock and to predict the aftershocks occurrences [4]. The basic idea is that an area experiencing a stress increase following a mainshock has a higher potential of aftershock events occurrence. The calculation of Coulomb stress change in this study is done using COULOMB 3.3. It is an open-source software developed by United States Geological Survey (USGS). The input parameter required for this modeling is fault geometry and in-situ stress.

Fault plane for the modeling in this study is derived from the focal mechanism solution and geological condition in the area. Fault geometry is obtained using empirical equation from Wells and Coppersmith [5]. We assume that the earthquake location as a bottom of rupture plane, as it is expected that the central source should be shallower than the hypocenter depth. We use the focal mechanism for Model 1 and 2, from, respectively, NIED and NEIC.

Table 1. Fault plane parameter used for the Coulomb stress change modelling.

|        | Model 1         | Model 2                  |
|--------|-----------------|--------------------------|
| Strike | N51°E           | N231°E                   |
| Dip    | 50°SE           | 87°SE                    |
| Rake   | 58°             | 3°                       |
| Slip   | Oblique reverse | Left lateral strike slip |

In-situ stress parameter consists of the orientation and magnitude of principal in-situ stress. The orientation of principal stress used in this study is taken from World Stress Map (2016) [6]. Meanwhile, the magnitude in-situ stress of this region was obtained from the previous studies [7,8,9]. The input in-situ stress data for the modelling is listed in Table 2.

Table 2. In-situ stress parameter used for the Coulomb stress change modelling.

|                                  |               |
|----------------------------------|---------------|
| Magnitude gradient of $S_{Hmax}$ | 341.57 bar/km |
| Magnitude gradient of $S_V$      | 212.63 bar/km |
| Magnitude gradient of $S_{hmin}$ | 174.18 bar/km |
| Orientation of $S_{Hmax}$        | N9°E          |
| Friction coefficient             | 0.4           |

For the aftershocks data, we compile a new catalog of seismicity by combining five catalogs, Indonesian Meteorological, Climatological and Geophysical Agency (BMKG), International Seismological Center (ISC), USGS, Incorporated Research Institutions for Seismology (IRIS), and Husni [10]. The new catalog is limited only to earthquakes with depth less than 35 km. We took manual procedure to prevent a duplication data of the same event from different author. The new catalog contains earthquake data from 26 May 2006 until 23 December 2009. The distribution of aftershocks is shown in Figure 1. From the aftershock data, we interpret that the aftershocks have a NE-SW trendline. This is parallel with the fault model from [11]. So, the target fault for this modelling is N45°E/90° with rake 0°, assuming that the target fault is a left-lateral strike-slip fault.

#### 4. Results and Discussion

Figure 3 and 4 shows the results of Coulomb Stress Change from Model 1 and 2, respectively. We divided the depth range for this modelling based on the fault geometry. The first depth range is from the surface to the top of the fault, the second is from the top to the bottom of the fault, and the last is deeper than the bottom of the fault.

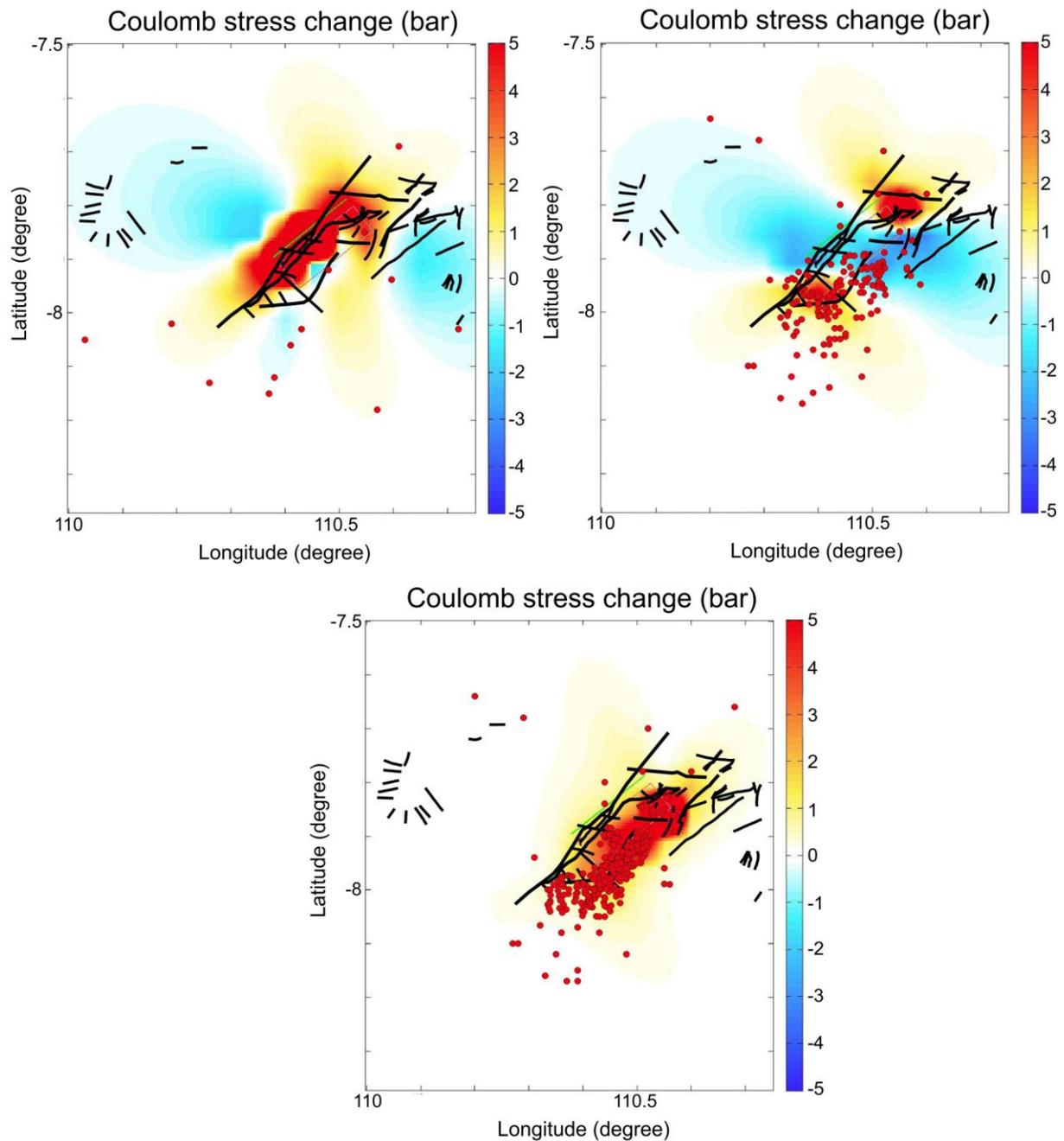


Figure 3. Map view of Coulomb stress change from Model 1 in the depth range of 0-3 km (top left), 3-10 km (top right), and 10-25 km (bottom center). The red dots indicate the aftershock events and the black lines represents the fault in the area.

Model 1 shows that the aftershocks pattern nearly fit with the distribution of positive stress change value. At a depth range between 3-10 km and 10-25 km, it is apparent that most of the aftershocks events gathers in the positive Coulomb stress change value. From this model, we can interpret the earthquake source is caused by reverse fault and the aftershocks is generated by strike-slip fault movement deeper than 10 km.

In model 2, the aftershocks pattern does not fit with the distribution of positive stress change value. At depth of 2-13 km, the aftershocks are located in the area with negative value of stress increase which indicate incompatibility of the theory proposed in Model 2.

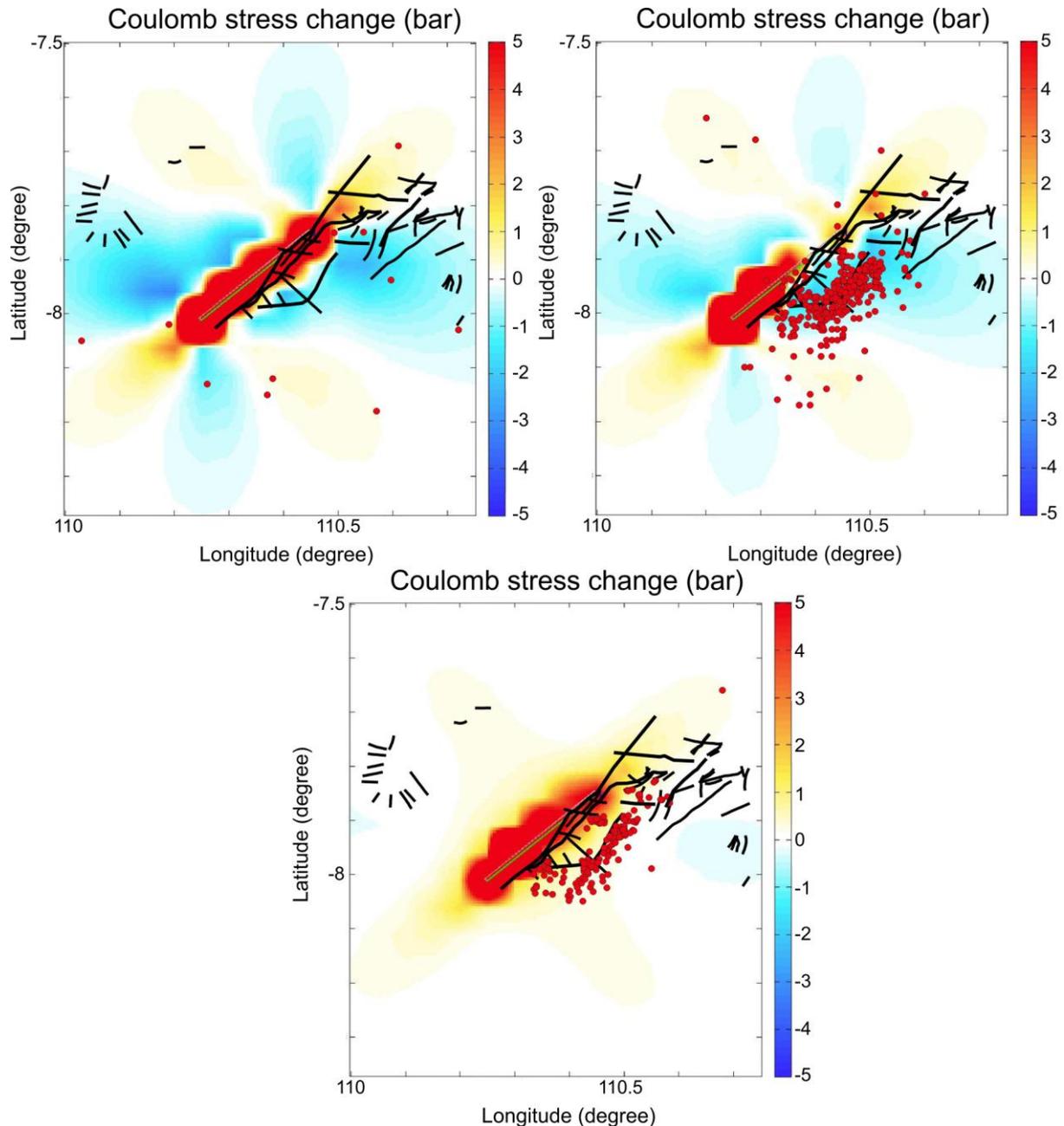


Figure 4. Map view of Coulomb stress change from Model 2 in the depth range of 0-2 km (top left), 2-13 km (top right), and 13-25 km (bottom center). The red dots indicate the aftershock events and the black lines represents the fault in the area.

On the A-B cross-section (Figure 5), we can see that the positive stress change value mainly distributed to the west of the fault. This is consistent with the earthquake damage distribution in which Bantul area (located west of Opak fault), suffered the heaviest damage. Furthermore, we also find an interesting agreement between our stress modeling and the distribution of aftershocks. There is a seismic gap zone in Beji, Gunung Kidul Regency which is located in a negative stress change value

(the area releases stress and does not possess the potential of producing aftershocks) in C-D cross-section (Figure 5).

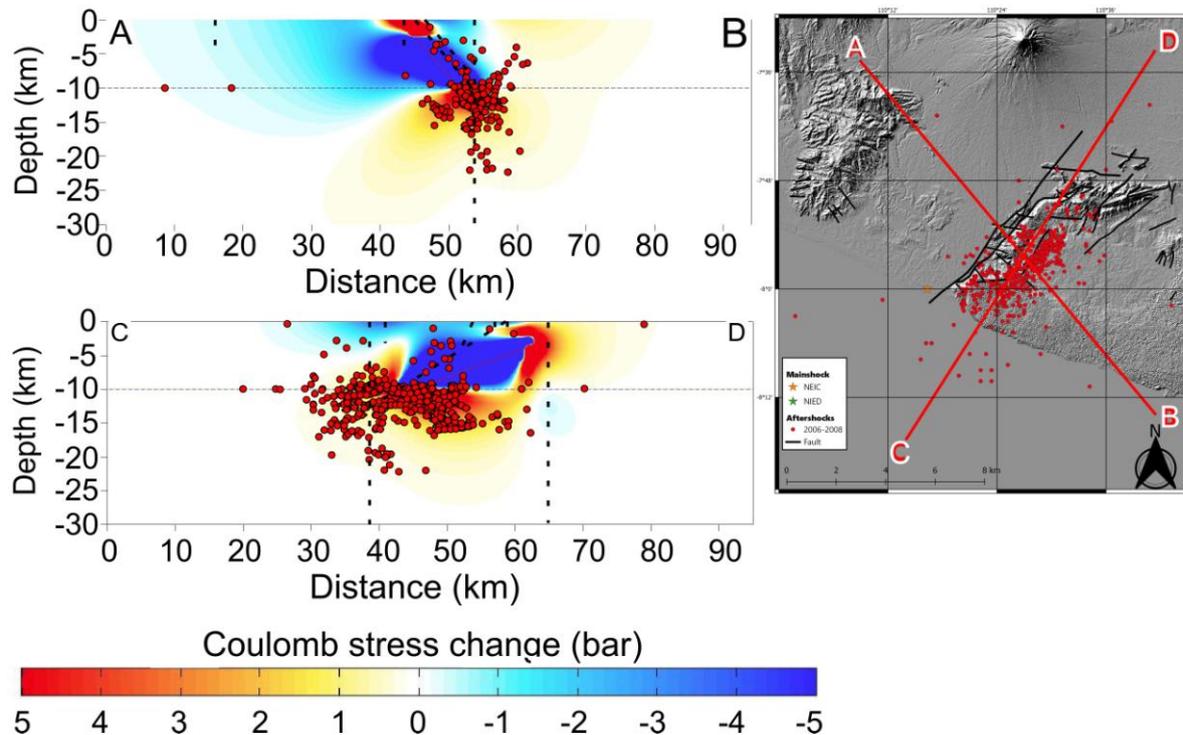


Figure 5. Cross-section of Coulomb stress change along lines A-B (top) and C-D (bottom). The red lines indicate the ruptured fault plane of the earthquake based on Wells and Coppersmith (1994). The aftershocks are plotted as red dots. The black lines represent fault.

## 5. Conclusions

Based on our Coulomb stress change modelling, we showed that Model 1 could better explain the mainshock and aftershocks of 2006 Yogyakarta earthquake. This model is an oblique reverse slip, with strike, dip and rake derived from NEID catalog. It suggests that the complex Opak fault is a flower structure (strike-slip) type. This conclusion was derived from the agreement between the distribution of the stress increase zone obtained using model 1 and the concentration of the aftershock events. Furthermore, this model could also explain the heavy damaged area observed in the western part of the Opak fault.

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