# Coulomb stress changes due to Queensland earthquakes and the implications for seismic risk assessment

## D. Weatherley

University of Queensland

## *Abstract*

Coulomb stress change analysis has been applied in numerous seismically active regions of the globe. These studies demonstrate categorically that the timing and rates of future earthquakes are affected by the static stress changes due to nearby historical earthquakes. This has significant implications for seismic hazard assessment and earthquake forecasting. Static stress interactions result in significant spatio-temporal variations in seismicity patterns, calling into question the reliability of estimates of long-term seismicity rates based on relatively short historical earthquake catalogues. Furthermore, the probability of earthquakes in some regions may be significantly reduced or enhanced depending on the proximity to earthquakes in the recent past. In Australia there has been much debate as to whether static stress changes should be considered when assessing the seismic hazard within the continent. We examine patterns of static stress change due to past M>4.5 earthquakes in Queensland. Due to insufficient observations to constrain the focal mechanisms, we employ assumptions on the orientations, rupture lengths and average slip associated with each earthquake in order to calculate stress changes. Although preliminary and involving a number of assumptions, the results demonstrate that past M>4.5 earthquakes have occurred in sufficiently close proximity for static stress interactions to occur. We also show that earthquakes along either of a pair of reverse faults bordering uplifted blocks tend to promote the occurrence of subsequent earthquakes along the other reverse fault. One hypothesises that the seismicity of such regions may be dominated by pairs of reverse faulting earthquakes, occurring within a relatively short interval compared with the average recurrence interval of the earthquakes.

## *Introduction*

In recent years significant progress has been made in forecasting the locations of aftershocks and subsequent mainshocks by considering the theoretical stress changes induced by past earthquakes (King et al., 1994). The technique, known as Coulomb stress analysis, assumes that an earthquake may be modelled as a slip dislocation within a uniform elastic half-space. By utilising analytic solutions for the displacement and stress in the surrounding medium and assuming that subsequent earthquakes result from frictional instability along pre-existing faults, one may compute the amount by which faults are brought closer to, or removed further from, brittle failure.

 Coulomb stress analysis places firm constraints on the regions most likely to experience aftershocks in the days following a mainshock. Most notably, the analysis predicts an increased probability of so-called "off-fault" aftershocks, occurring some distance from the mainshock hypocentre. These off-fault aftershocks are of considerable concern during relief efforts as these typically occur along fault segments that are already pre-stressed, resulting in larger magnitudes than aftershocks within or near the rupture zone.

Coulomb stress analysis also offers the possibility to calculate the time-evolution of stress within a fault system and to predict the regions with heightened probability of mainshocks in the near future. A classic demonstration of this potential is the successful forecast of the 1999 Izmit, Turkey earthquake (Parsons et al. 2000) and the analysis of Coulomb stress changes due to M>7 earthquakes along the North Anatolian Fault during the 20th Century. Static stress triggering of mainshocks is expected to give rise to time-dependent recurrence statistics. The probability of occurrence of mainshocks of a given magnitude will depend upon the recent seismic history in the surrounding region.

Traditional approaches for estimating recurrence statistics, based upon the Gutenberg-Richter relation do not take account for this time-dependency of earthquake occurrence.

There has been some debate as to whether stress interactions need be considered when estimating the seismic risk of the Australian continent. This paper constitutes a first step towards addressing this issue. We examine the theoretical stress change patterns of past Queensland earthquakes and demonstrate that subsequent seismic activity has occurred within sufficiently close proximity for stress interactions to occur. We also consider the stress changes induced by two hypothetical earthquakes of M=5 occurring on conjugate reverse faults, bordering an uplifted Block in south-east Queensland. The analysis suggests that such earthquakes may be cooperative in the sense that an earthquake on one fault will increase the Coulomb stress within the seismogenic zone of the other fault. A dearth of focal mechanisms and detailed structural information necessitates the use of arguably crude assumptions on the orientation and rake of the modeled earthquakes; however the results clearly demonstrate the potential for static stress interactions between faults in eastern Queensland.

## *Methodology*

The procedure for computing the Coulomb stress changes due to an earthquake is well described by King et al. (1994). The appropriate starting point is to model the earthquake as a slip dislocation on a rectangular fault plane (or planes) representing the earthquake source zone. One may then compute the change in both shear and normal stress caused by the earthquake, utilising the Okada (1992) analytic Green's Function for stress changes due to rectangular dislocations in an uniform, elastic half-space. If one further assumes an orientation for faults in the region surrounding the earthquake, one may compute the net change in Coulomb stress along these surrounding faults. Coulomb stress is defined as the difference between the shear stress ($\tau$) and the normal stress ($\sigma$) multiplied by an effective coefficient of friction ($\mu^{(eff)}$), namely:

$$CFS = \tau - \mu^{(eff)}\sigma$$

An increase in Coulomb stress on a fault may thus be interpreted as a loading of the fault towards brittle failure (i.e. earthquake rupture). Conversely, a decrease in Coulomb stress is interpreted as an unloading of a fault, thus inhibiting earthquake rupture. Although earthquakes indisputably result in an overall decrease in the net stress accumulated in a region, the patterns of stress change are such that certain regions surrounding a given earthquake experience an increase in stress. Most notably there is a marked Coulomb stress increase in the zone surrounding the rupture plane (the zone most likely to experience aftershocks) and two or more off-fault lobes where delayed triggering of subsequent mainshocks may occur.
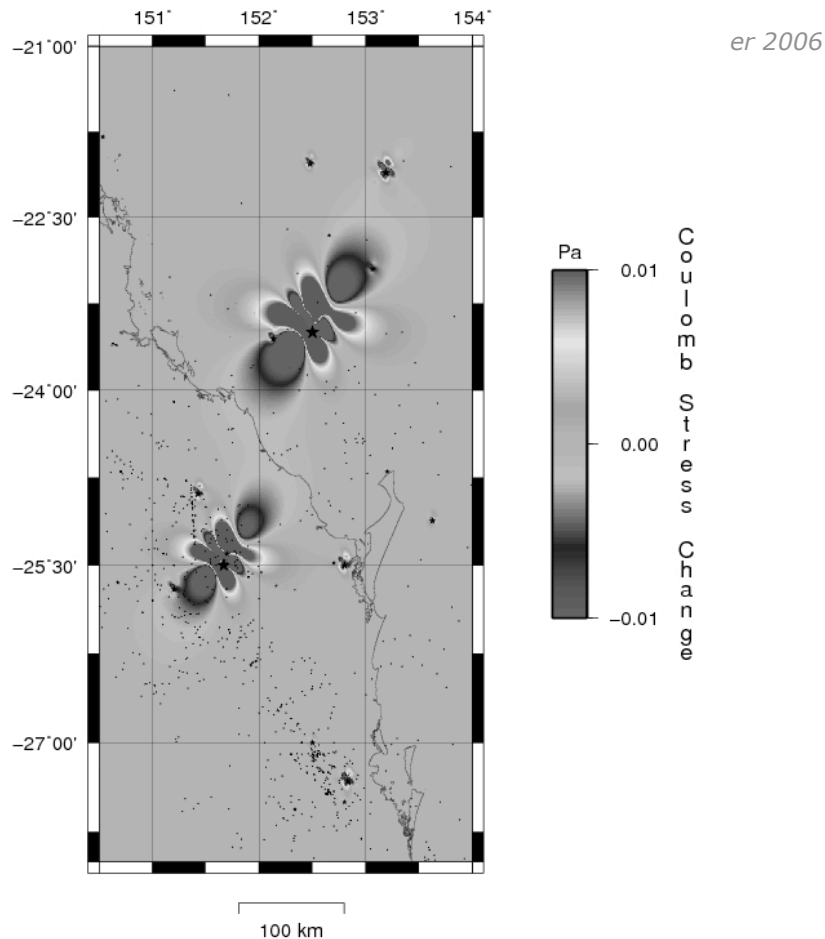
Figure 1: Coulomb stress changes due to M>5 earthquakes in
Southern and Central Queensland.

In this work we have employed the 3ddef software to compute stress changes due to modelled earthquakes. This software permits the specification of the earthquake source in terms of a rectangular plane in 3D with a prescribed average slip dislocation across the fault plane. We have selected for analysis all earthquakes of magnitude M>4 in the Queensland earthquake catalogue. The rupture zone of each earthquake is a square of side-length L, extending from a depth of 10km with an average slip (u) across the fault plane. We utilise the following scaling laws (Papadimitriou and Sykes, 2001) to determine the rupture length (L) and average slip (u) for each earthquake:

$$LogL = 0.51M - 1.85 \qquad logu = 0.82M - 3.71$$

Due to a lack of focal mechanisms for these earthquakes we are unable to adequately constrain neither the strike and dip angle of the fault planes, nor the rake of the earthquakes. Examination of geological maps for the regions of interest reveals a general trend of N30W striking faults displaying oblique reverse-faulting tendencies. From available transects, the dip angles of faults range between near vertical and up to 45degrees to either the East or West. In south-east Queensland for example, the West Moreton Fault dips towards the east while the North Pine Fault dips towards the west. In the following analysis we assume that all earthquakes strike N30W and model the earthquakes with either pure strike-slip or pure dip slip for a range of easterly and westerly dip angles.

Having specified the source parameters for each earthquake, we compute the static stress changes via 3ddef. From the computed static stress changes we compute the theoretical Coulomb stress change along fault planes oriented parallel to the earthquake source (in the surrounding region). This amounts to calculating the net change in both shear and normal stress along the specified fault planes. We assume here that the effective coefficient of friction of all faults is approximately 0.4. Coulomb stress

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calculations are relatively insensitive to the choice of effective friction coefficient so this value is considered reasonable (King et al. 1994).

## *Results*

We commence by examining the Coulomb stress changes due to past M>5 earthquakes in South and Central Queensland. To simplify the investigation we have a priori constrained the dip angle of all fault planes to 45 degrees, dipping to the east. We compute the Coulomb stress change along faults oriented at N30W at a depth of 5km. The results are shown in Figure 1, overlain with the epicentres of all past earthquakes in the Queensland seismic catalogue. The 1935 Gayndah earthquake (M=6.1) and the 1918 offshore Gladstone earthquake (M=6.3) dominate in Central Queensland. It is evident that these two largest earthquakes are sufficiently close to form a "stress bridge" across the Queensland coast near Gladstone. Isolated M>5 earthquakes also result in more localised Coulomb stress changes including at least three M>5 earthquakes lying within the stress change lobes of the two M>6 earthquakes. In all cases, a number of recorded earthquakes lie within or near regions of large Coulomb stress change.

There is no question that the assumption of eastward dipping reverse faults is rather crude. A much closer inspection of the local geology and focal mechanisms (where available) is required to accurately model the stress changes due to past earthquakes. The results in Figure 1 simply demonstrate that stress changes of up to 0.01 bar are expected at sufficiently large distance from the rupture planes of past earthquakes that the timing of nearby earthquakes may be altered by static stress interactions.

In many parts of eastern Queensland and other regions in Australia, the structural geology is dominated by pairs of eastward and westward dipping reverse faults, bordering an uplifted block. One such example is the South D'Aguilar Block in south-east Queensland, bordered to the west by the easterly dipping Eastern Border Fault and to the east by the westerly dipping North Pine Fault. Figure 2 is a caricature of the three dimensional fault structure of the region. The 1960 M=5.0 Mt Glorious earthquake is thought to have ruptured a portion of the North Pine Fault.

We shall examine the static stress changes induced by a pair of hypothetical M=5.0 earthquakes rupturing a 5km x 5km patch of the Eastern Border and North Pine Faults (marked as coloured squares in Figure 2). A net slip of 2.4cm is applied across each fault plane with the slip direction selected to promote uplift of the region between the two faults. The rupture planes commence at a depth of 5.25km and extend to almost 10km depth (the assumed depth of the seismogenic zone) dipping at an angle of 30 degrees to vertical. The epicentre of the North Pine earthquake is within 10km of the Mt. Glorious earthquake epicentre.

Figure 3 contains snapshots of the Coulomb stress change induced by these earthquakes for a sequence of horizontal cross-sections of increasing depth. For shallow depths, the two earthquakes induce Coulomb stress increases along parallel faults outside the South D'Aguilar Block, with only a slight Coulomb stress increase within the Block due to slip near the base of the rupture planes. As depth increases, the lobes of increased Coulomb stress migrate into the Block, with positive CFS lobes dominating within the block for depths greater than 7.5km.
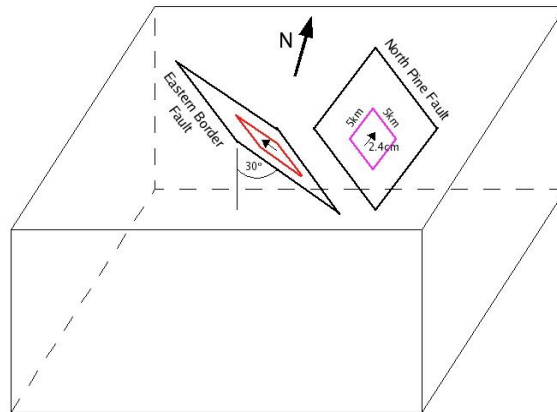
Figure 2: A diagram of the 3D fault structure in the region of the South D'Aguilar Block, SE Queensland.

## Conclusions

Two important facts arise from these calculations. Firstly, the static stress changes will promote the occurrence of shallow focus aftershocks outside of the South D'Aguilar Block. Since shallow aftershocks are expected to have a higher damage potential, this is a valuable constraint for post-mainshock mitigation efforts. Secondly, positive Coulomb stress changes at seismogenic depths of between 5 and 10km are focused towards the fault plane on the opposite side of the South D'Aguilar Block. In essence, a reverse faulting earthquake on one side of the Block promotes the occurrence of an earthquake on the other side of the Block and vice versa. While the Coulomb stress increase for a M=5 earthquake is very small (less than 0.001bar), a larger magnitude (M>6) earthquake may result in between 0.01 and 0.1bar Coulomb stress increases. An increase of this magnitude is comparable with that shown to result in static stress triggering in other seismogenic regions and hence must be considered in seismic hazard assessment, particularly the calculation of recurrence times or probabilities.

Although preliminary in nature, these results highlight the need to consider static stress interactions when estimating the seismic hazard in Eastern Queensland. Past earthquakes have occurred within sufficient proximity of mainshocks for static stress interactions to affect their timing. Furthermore, earthquakes with M>5 occurring on conjugate reverse faults promote the occurrence of mainshocks on opposing faults. Further research and modelling is required to quantify the long-term impact of such stress changes. One may hypothesise that seismicity patterns may be dominated by episodic occurrence of "twin" mainshocks rupturing either side of uplifted blocks, separated by relatively long periods of seismic quiescence.

## Acknowledgments

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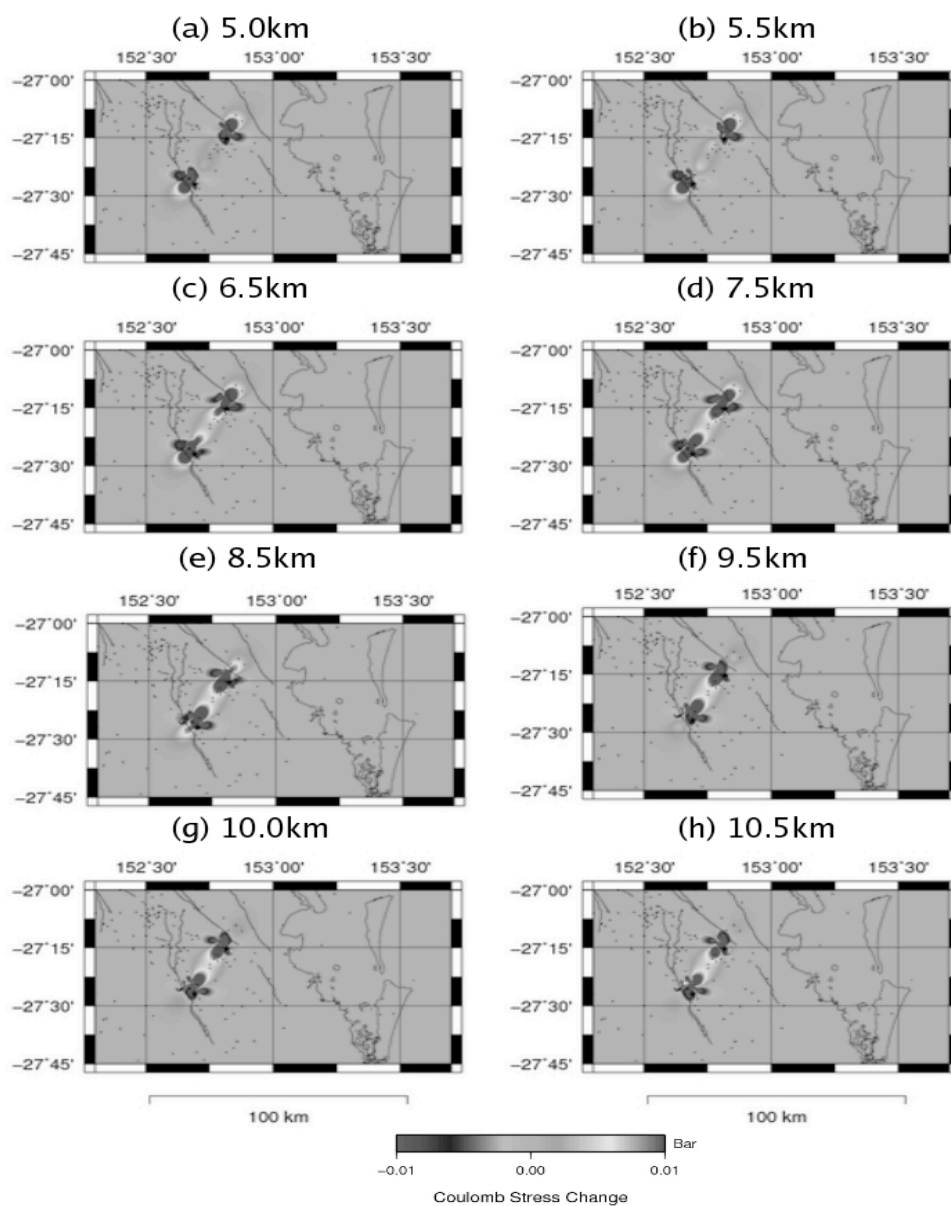
Figure 3: Coulomb stress change within horizontal planes at various depths.