Static Stress Changes and Fault Interaction Related to the 1985 Nahanni Earthquakes, Western Canada

ALI O.ONCEL
Earth Sciences Department
King-Fahd University of Petroleum&Minerals
P.O.Box 1946, Dhahran 31261
SAUDI ARABIA
http://faculty.kfupm.edu.sa/ES/oncel/

Abstract: - The 1985 Nahanni earthquakes (05/10/1985, Mw=6.6; 23/12/1985, Mw=6.8) were the largest observed events of the past 100 years not only in the Nahanni region of Canada but in the NE Cordillera. Their short interevent period (about two months) between the two mainshocks and their shallow depth (about 8 km) make them interesting since those characters for seismicity has rarely been reported. I compute the changes in static stresses along optimally oriented planes, caused by these events using the slip models of Hartzell et al. [1994] for the mainshock sources to investigate the possibility of dip-slip interaction and compare the relation between the patterns of aftershock seismicity and static stress. Thus, I then combine our coseismic stress changes with the regional stress to determine the induced stress changes for explaning short-term field-recorded aftershock seismicity nearly in one month and medium-term seismicity (1985-2002). The static stress change generated by the 5 October event onto the fault plane of December event are calculated and concluded that the occurrence of the 23 December Nahanni event seems triggered since the shallow major asperity along the fault plane is appeared to be induced by stress due to October earthquake but the deep intermediate asperity, which is very near to epicenter, seems partly discouraged, that may be a cause for delaying the onset time of December event for about two months. Subsequently, in 1988, a large event (M6.2) and its aftershocks, occurred in a region where the static stress level was increased by the 1985 Nahanni earthquakes.
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Key-Words: Coulomb Stress, Fault Modeling, Interaction, Shadow Zone, Earthquake

1 Introduction

Understanding short-term variability of seismicity parameters are very important to have some insights on short and medium-term seismic hazard especially for active-faults of stable tectonics. Thus, earthquake-induced static stress changes based on dislocation models of fault-slip provide a mechanism for understanding the spatial variability of aftershocks [e.g., 1, 2]. Modeling of short-term seismic hazard, based on the Coulomb-failure approach appears to be a tool for defining the potential locations of future mainshocks [e.g., 3; 4; 5; 6; 7] as well as comparing to recent seismic activity.

I test this hypothesis with data from a cluster of large earthquakes in Canada. The 1985 Nahanni earthquakes (05/10/1985, Mw=6.6; 23/12/1985, Mw=6.8) were an unexpected sequence of large earthquakes in the Northwest Territories of Canada, a region with no record of historical large earthquakes [8]. Two smaller events (14/08/1974-MN=4.1 and 14/01/1977-MN=2.8, where MN is Nuttli magnitude, used to measure eastern Canada earthquakes) had occurred in the Nahanni region in the previous 12 yrs, a possible sign that the area was preparing for future seismic activity. The time (79 days) and distance (5 km) between the two large 1985 earthquakes (at depths of about 8 km) suggest a physical relationship between the two events. In this paper, static stress changes generated onto dipping plane by the 1985 Nahanni events (Fig.1) are examined to explain the aftershocks of 1985-1986 and subsequent mainshocks.

2 Problem Formulation

2.1. Data

Defining fault rupture planes for Canadian earthquakes is not easy and is seldom obvious due to the general lack of surface rupture. Despite this challenge, the aftershock surveys by the Geological Survey of Canada provide significant clues for choosing the rupture planes of the Nahanni events [9]. In addition, similar rupture parameters for the 1985 Nahanni events are found by Hartzell et al. [10], Choy and Boatwright [11] and Wetmiller et al., [9], providing encouragement that these are robustly modeled events whose effects I can examine in the near-field. In this paper, I use the

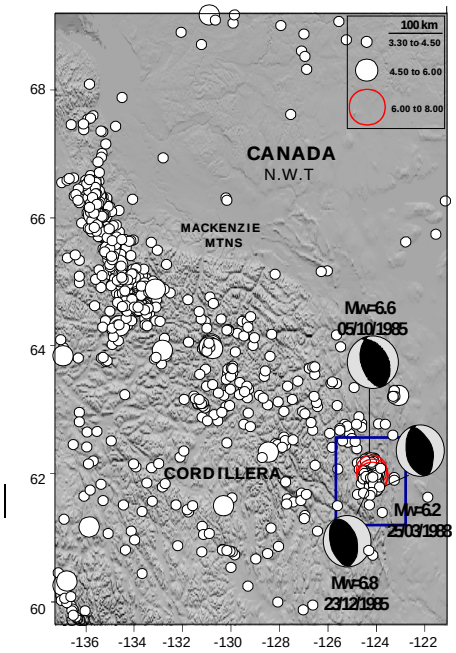

Fig.1. Seismicity map of the Nahanni fault zone for earthquakes with MN>3.3 between January 1985 and June 2002. Harvard focal mechanisms solutions for two events are located in the map. The square are shows the enlarged region in Fig.3.

variable slip models of Hartzell et al., [10] for the 1985 earthquakes. These slip models are based on teleseismic body waves as well as the strong-motion records obtained by the Geological Survey of Canada [12] and the velocity model derived from industry data [13] [Steve Hartzell, personal comm., 2002]. The slip model parameters are mapped and tabulated for each rupture (Table 1).

The slip model of the 5 October 1985 Nahanni event has 150 subfaults, with 10 subfaults down-dip and 15 subfaults along-strike. The slip model of the 23 December 1985 Nahanni event has 162 subfaults, 9 down-dip and 18 along-strike. The slip plots in Fig.2 have been smoothed. Aftershocks of the 1985 Nahanni events were recorded in the field for four days from October 13-17, 1985 for five days from January 3-8, 1986 and for nine days from September 12-21, 1986 [9] and 7-15 May, 1988. These aftershock data are compared with the earthquake-induced stress changes.

3 Problem Solution

3.1. Method

I compute Coulomb stress changes for slip on a rectangular fault in a homogeneous half-space [14; 15; 16] as:

$$\Delta CFS = \Delta\tau + \mu' \Delta\sigma \qquad (1)$$

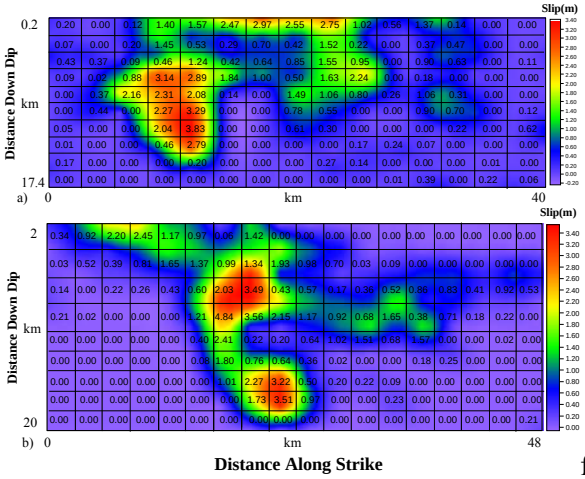

Fig.2. Contoured slip subfaults and asperities, in meters for a) the 5 October Nahanni earthquake, the area of the largest asperity is 46 km^2 and its average slip is 2.51 m and b) the 23 December Nahanni earthquake. The area of the largest asperity is 31 km^2 and its average slip is 2.7 m.

where apparent friction $\mu'=\mu[1-\beta]$. $\mu$is the coefficient of friction, $\Delta\sigma$is the induced change in normal stress, with positive values indicating increased tension, $\Delta\tau$is the induced change in shear stress in the rake direction, and $\beta$is Skempton's coefficient. When and where $\Delta CFS > 0$, an event is said to be encouraged, enhanced or triggered by a preceding event; when and where $\Delta CFS < 0$, an event is said to be discouraged or in a shadow zone from a previous event. In this study, $\mu=0.4$ and $\beta=0.5$ are used. I used the program GNStress1_5, written by Russell Robinson based on the subroutines of Okada [15], to calculate ΔCFS. In order to estimate stress "on optimally oriented faults" option, I use the azimuth for a regional stress field for most (S1) and least (S3) principal stress axis of oriented 65°±25° and 155°±25° respectively [17], the dip for S1 and S2 are considered as °0 degree and 90° degree. Thus, values S1 (compression in negative) and S2 for regional stress in Mpa are used as -10 MPa and 10 Mpa while S2 is used as 0 MPa in order to provide the requirement as S1<S2<S3. The effects of a range of friction values (μ=0,0.4,0.8) were tested. The shear modulus for stress calculation is estimated and shown as bar through the related figures of current paper.

3.2. Results

3.2.1. Static stress changes caused by the Nahanni October 5,1985 earthquake

The aftershock pattern projected onto a dipping

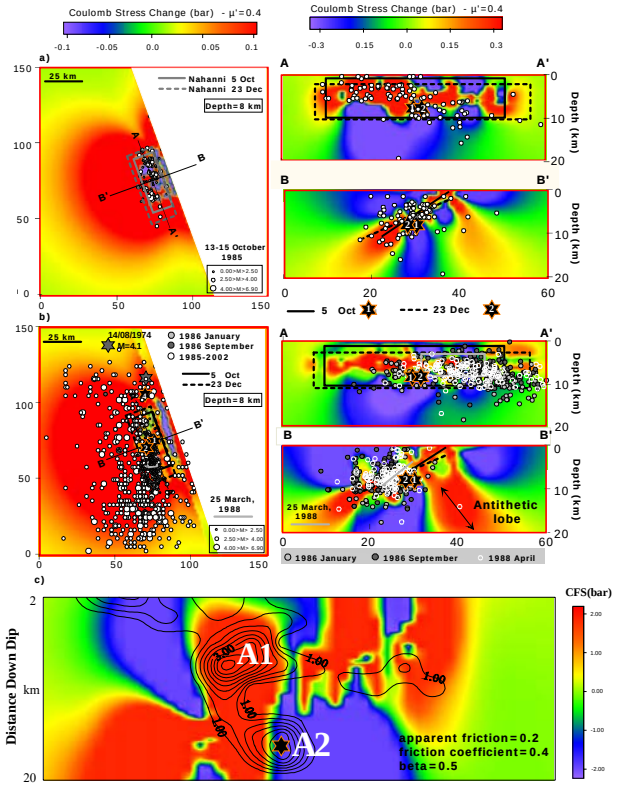

Figure 3. a) Coulomb stress maps for the event of October 5, 1985 (star labeled "1"). The Coulomb stress changes are shown resolved on horizontal planes at 8 km depth and onto 2 vertical crossections (at larger scale) . Red oblong / bar represents rupture plane of March 1988. ΔCFS=±0.1 bars for the map view side and 0.3 bars for the vertical sections.The white circles are the field-recorded aftershocks. Star labeled "2" locates subsequent December mainshock. b) The combined Coulomb stress changes due to the Oct and Dec, 1985 mainshocks are compared to the March and May 1988 mainshocks and the seismicity for October 1985-December 2002 as determined from the regional seismograph network. The combined stress changes are also compared in the vertical sections A-A' and B-B' to the aftershocks (black circles) of the March 25, 1988 mainshock . c) Coulomb stress change onto fault plane of December 23 event due to Ocotober 5 event.

plane at depth of 8 km is well explained by the Coulomb stress changes on best oriented planes through the dipping plane due to the spatially-variable slip distribution (Figure 2) of the Nahanni Oct 5 1985 mainshock. The broad stress enhancement zone is located mainly along strike while the shadow zone appears transverse to the strike (Fig.3a). In addition, the changes of Coulomb stress on best oriented planes along the vertical plane (B-B') indicate that the stress model mostly matches the aftershock locations. The rupture plane of the following mainshock (Dec 23, 1985) is shown on the calculated stress change map and corresponds to zones of increased stress.

There is more seismic activity where the stress is calculated to have increased and less activity where the stress is calculated to have decreased. Thus, the explanation of a gap in seismicity [Wetmiller et al., 1988] along the fault strike may be explained by a shadow zone inhibiting seismic activity at 8 km depth just east of intersections AA' and BB'.

3.2.2. Combined Static stress changes due to 1985 earthquake Nahanni earthquakes

The stress changes through the dipping plane due to the December 23, 1985 earthquake are calculated using the spatially-variable co-seismic slip distribution from Hartztell et al., [10] (Figure 2) and superimposed to the stress due to October 5, 2005 earthquake (Figure 3b) since the stresses due to both events were similar as the absence of aftershocks in antithetic lobes . The calculated positive stress matches the locations of the recorded aftershocks while calculated negative stress is appeared to be agreement with the seismic gap (Figure 3b). Thus, the lack of seismicity in the shallower part of the crust (see A-A', Figure 3b) is found to be controlled by the shadow zone. The aftershocks along the dip plane (B-B') are located in the center of the dipping plane and seismicity growth is stopped towards the edges of the dipping plane. Furthermore, increased shear stress without seismicity in the antithetic lobe is observed, similar to previous observations [e.g., 5].

3.2.3. Dip-slip interaction between 1985 Nahanni events

The two events considered are here named E1 (05/10/1985, Mw=6.6), E2 (23/12/1985, Mw=6.8) through the following section. Now, I want to investigate the interaction between E1 and E2 by evaluating the stress field perturbation created by E1 on locations distributed along the E2 fault plane (e.g. E2 hypocenter), as robustly modeled by previous studies [5] since evaluating the stress on horizontal map at 8 km depth or vertical sections such as AA' and BB' in Figure 3a may not be found very convincing since the two faults of E1 and E2 are too near to appreciate the regions of stress increase. Moreover since the strike, dip and rake angle of the E2 event are known, than the secondary plane is known in this case. For evaluating the E1-E2 fault interaction, I projected static stress changes

and normal stress changes on the E2 fault plane and slip direction.

I assumed the E2 fault plane as secondary fault plane to project the stress change due to E1 onto the E2 fault plane and evaluated that the area of shallow asperity (A_1) have been largely positive but the deeper asperity (A_2), which nearly corresponds to the epicentral area, is observed partially surrounded by blue area (see Figure 3c). This is may be mainly due to the fact that the E1 and E2 faults are not nearly subparallel since differences on their dips are suggested to be an indicator of a listric fault since E1 has a larger dip of 35 than the dip of 25 degree for E2 (see Table 1).

Table 1. *Orientation of fault planes and model rupture parameterization.*

Event	Subfault	Strike	Dip	Total number	Rake	L	W	Depth of	Depth of	M_0	Slip model
	Dimensions			of subfaults				top	bottom	xE26	reference
	(km)					(km)	(km)	(km)	(km)	dyn-cm	
5/10/1985	2.66 by 1.74	160	35	150	90	40	10.2	0.2	10.2	1	Hartzell et al., 1994
23/12/1985	2.66 by 2.36	160	25	162	90	48	20	2	11	1.5	Hartzell et al., 1994

4 Conclusion

The combined static stress changes caused by the summed effects of the October and December 1985 Nahanni earthquakes are shown in Figure 3c. I now examine if the subsequent 25 March 1988 SE Nahanni (Mw=6.2) and the 22 May 1988 NW Nahanni (Mw=5.0) events might have been triggered by the previous larger Nahanni earthquakes. ISC depths of the 1988 events are 10.18±2.63 km and 8.86 ± 4.39 km respectively but unpublished aftershock data [R.J. Wetmiller, personal comm., 2002] indicate that the depth for the March event is 6-8 km similar to the depths of the 1985 events. Also, the focal mechanisms of the March and May 1988 earthquakes are essentially the same (strike=170-165 degrees, dip=39-32 degrees). The aftershocks of the March 1988 earthquake and its estimated fault projection [based on the relation of moment-fault dimension relation, 18] are located on the map of combined static stress changes. The aftershock cluster of the March 1988 event seems to extend beyond the likely rupture plane and so occur on a plane activated by the 1985 events, and the March 1988 therefore was probably triggered by the previous events. Moreover, the May and March 1988 Nahanni events occur at opposite ends the 1985 fault ruptures and so are evidence of bilaterally activated along strike stress enhancements.

Subsequent changes in seismicity (1985-2002) appear related to the pattern of co-seismic stress changes due to 1985 Nahanni earthquakes along their dipping planes with SE-NW ruptures (Figure 3b). A bilateral increase in stress loading is indicated by (i) the March and May 1988 mainshock locations, (ii) the larger post 1985 events occur to the south; (iii) the pattern of regional seismicity. The four largest post-December 85 events occur in the southern zone are, related to aftershocks of the 1985 Nahanni mainshocks and suggest unilateral rupture growth to the south [see Figure 4 of eg., Horner et al., 1990]. The March and May 1988 mainshocks, to the south and to the north of the 1985 events indicate a bilateral increase of seismic activity.

Coulomb failure theory and variable slip models are used to calculate Coulomb stress changes for large earthquakes in the Nahanni region of Canada. Stress interactions between the Nahanni events are calculated through the dipping plane rather than flat plane since the stress change models are compared better to the aftershock data which are distributed along dip. Thus, in 1988 mainshocks of Mw=6.2 and Mw=5.2 occurred south and north of the 1985 rupture zone earthquakes possibly indicating an increase in the seismic hazard in the along-strike direction. In general, the zones of shadow and stress enhancement along fault dip and strike appear to govern the locations of the aftershocks. A previously proposed seismic gap or zone of quiescence in this region can be explained by a stress shadow zone. In contrast, aftershocks are clustered in the zones of stress enhancement. The pattern of subsequent 1988-2002 earthquake activity appears to be similar to the aftershock pattern and indicates that seismicity in the region continues to be affected by the stress changes due to the Nahanni events.

Stress changes is computed on the E2 fault plane to understand the E1-E2 fault interaction than the analysis (see Figure 3c). Stress through the largest asperity of E2 in shallower depth has been largely observed to have increased while stress through the intermediate asperity, which is suggested to be center for earthquake epicenter, is partially appeared to have decreased, that may be a cause a delay of about two months for the onset time of December 23 event.

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