

Geomechanical modeling of the nucleation process of Australia's 1989 M5.6 Newcastle earthquake

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Abstract

Inherent to black-coal mining in New South Wales (Australia) since 1801, the discharge of ground water may have triggered the M5.6 Newcastle earthquake in 1989. 4-dimensional geomechanical model simulations reveal that widespread water removal and coal as deep as a 500 m depth resulted in an unload of the Earth's crust. This unload caused a destabilization process of the pre-existing Newcastle fault in the interior of the crust beneath the Newcastle coal field. In tandem, an increase in shear stress and a decrease in normal stress may have reactivated this reverse fault. Over the course of the last fifty years, elevated levels of lithostatic stress alterations have accelerated. In 1991, based on the modeling of the crust's elastostatic response to the unload, there has been the minimal critical shear stress changes of 0.01 Mega Pascal (0.1 bar) that reached the Newcastle fault at a depth where the 1989 mainshock nucleated. Hence, it can be anticipated that other faults might also be critically stressed in that region for a couple of reasons. First, the size of the area (volume) that is affected by the induced stress changes is larger than the ruptured area of the Newcastle fault. Second, the seismic moment magnitude of the 1989 M5.6 Newcastle earthquake is associated with only a fraction of mass removal (1 of 55), following McGarr's mass-moment relationship. Lastly, these findings confirm ongoing seismicity in the Newcastle region since the beginning of the 19th century after a dormant period of 10,000 years of no seismicity.

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1. Introduction

Several historical examples show that mining activities disturb the in-situ stress in the upper continental crust and can trigger earthquakes (human-triggered seismicity). Since the beginning of the 20th century,

increased seismicity has been observed due to deep gold mining in South Africa [1,2]. In Germany, earthquakes related to mining have also been observed since the 19th century [3]. Potash mining, for example, caused the 1989 M5.6 Völkershäusen event in Germany [4]. Potash mining also triggered the 1986 M5.6 Provadia earthquake in Bulgaria [5]. In Silesia, copper mining initiated several earthquakes with magnitudes larger than $M=4$ [6]. Ore mining generated the 1989 M4.1 earthquake in the Khibiny Massif in the Russian Federation [7]. In the NE of the United States

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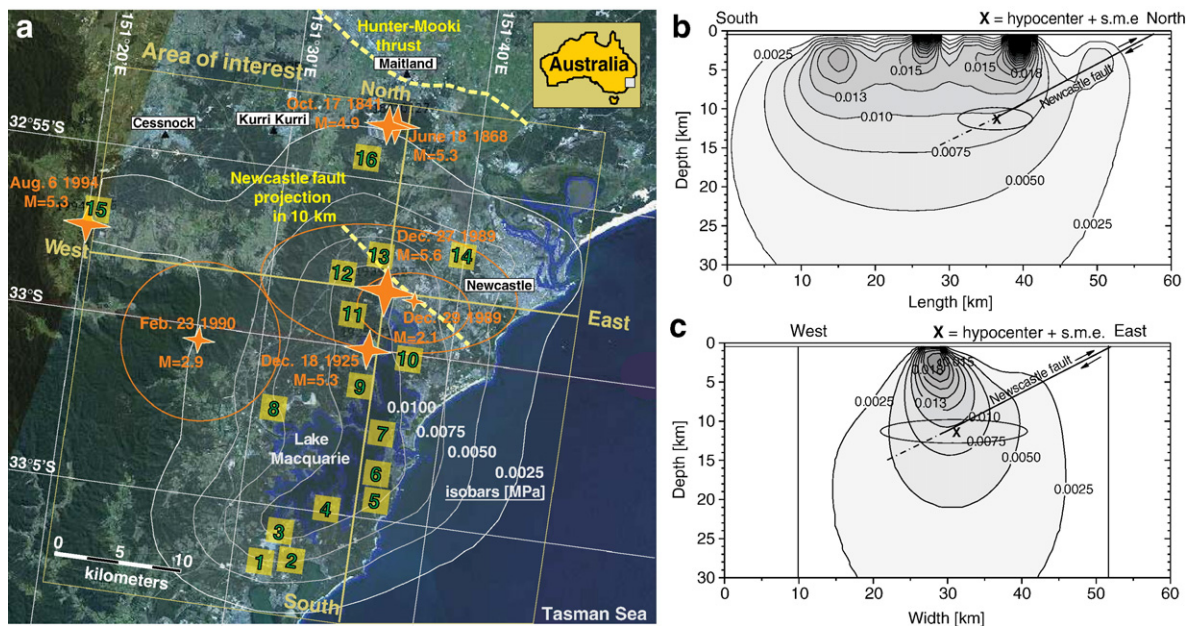


Fig. 1. Newcastle and the Newcastle coal field: (a) Satellite image of the area of interest near Newcastle* with 16 collieries of the Newcastle coal field (squares); epicenter \pm error of the Newcastle mainshock on December 27, 1989 (big diamond), the two aftershocks on December 29, 1989 and February 23, 1990 (small diamonds) and other earthquakes (medium diamonds); orientation of the Newcastle fault at 10 depth striking to $330\pm 10^\circ$ Northwest with a dip angle of $39\pm 3^\circ$; distribution of the shear stress isobars $\Delta\tau$ =[MPa] on 39° inclined volume elements at 10 km depth in 1989; traces of the N–S and W–E cross section in picture (b) and (c). The production data of the 16 collieries are given in Table 1. (b) Isobars of the shear stress $\Delta\tau$ along the N–S cross section and the hypocenter of the mainshock. (c) Isobars of the shear stress $\Delta\tau$ along the W–E cross section and the hypocenter of the mainshock. *Source: Australian Centre for Remote Sensing.

of America, surface mining triggered the Wappingers Falls earthquake sequence in New York State [8] and may have been the cause of the 1996 M4.6 Cacoosing Valley earthquake in Pennsylvania [9]. The 1995 M5.2 earthquake in southwestern Wyoming was associated with mining a trona (evaporite) deposit [10], while, coal mining prompted the M4.2 earthquake in 1994, near Beijing, China [11].

Black-coal mining was first started near Newcastle in 1799 [12]. Since 1950, demand for coal mining in Newcastle was determined by the growing energy consumption, worldwide. This paper shows that mass reductions at the sub/surface due to groundwater discharges, which are inherent to underground coal mining, can influence the lithostatic equilibrium of the shallow continental crust. The article gives an overview about the geological and tectonophysical situation near Newcastle. It details the history of the mining production, and the influence mining activities have to the stress field in the upper most part of the Earth's crust. Geomechanical modeling results exemplify how induced stresses could allow the coal field's underlying Newcastle fault to come closer to failure, in a depth where the 1989 M5.6 Newcastle nucleated.

2. Data and methods

2.1. The 1989 Newcastle earthquake

The Newcastle earthquake occurred on December 27, 1989 at 23:26:57 Universal Time (UTC). It was 19 km West of Newcastle at a depth of 10–13 km [13–15] and its epicenter was located at longitude $151^\circ 36' 25''$ East and latitude $32^\circ 57' 51''$ South with an uncertainty of 10 km E–W and 5 km N–S (Fig. 1). The main shock was of seismic moment magnitude of $M_w=5.6$ [14] followed by two aftershocks; December 29, 1989 ($M_L=2.1$) in 13.6 ± 0.8 km depth and February 23, 1990 ($M_L=2.9$) in 11.3 ± 10 km depth. Both seismological and geological observations [13,14,16,17] show evidence that the mainshock nucleated on the Newcastle reverse fault, striking $330\pm 10^\circ$ (mean \pm s.m.e) to Northwest with a dip angle of $39\pm 3^\circ$ (Fig. 1). The Newcastle fault at the Northeast boundary of the Sydney basin is probably the tip of an eastward extension of the Hunter–Mooki thrust zone [17,18,16]. This major fault system extends into the basin's Paleozoic basement and it separates the Sydney basin from the New England fold belt in the North-East [16].

2.2. 200 years coal mining near Newcastle

Surface mining is generally prevalent in Australia, whereas underground mines can be found in New South Wales, although their contribution has fallen from 100% in year 1950 to 20% in year 2000, based on raw-coal material. But, more than 90% of the collieries in the Newcastle coal field are still mined by longwall underground methods (Fig. 1). Mining occurs in depths between 150 and 500 m within Permian coal seams ≤ 600 m thick. It covers the bedrock at the northern margin of the Sydney basin [19]. From 1801 to 1989 more than 536 Mt coal was produced in the Newcastle coal field Southwest of Newcastle (Fig. 2a and Table 1).

Interpolation of annual production data is based on a Gaussian process model, whereby the cumulative coal production, e.g., between 1801 and 1980, is in agreement (1.4% difference) with official statistics [12]. Dewatering of 16 main underground mines, which are below or close to Lake Macquarie (Fig. 1), has been occurring since 1801. This is done to keep coal seams dry and to make longwall mining possible. Closed mines that were assumed to be immediately and entirely backfilled, were not analyzed to keep the modeling as simple as possible. In 1989, active collieries had maximum extensions of at least 2500×2500 m² and were mined on an average depth of 325 ± 175 m. Sediments above each colliery were permanently

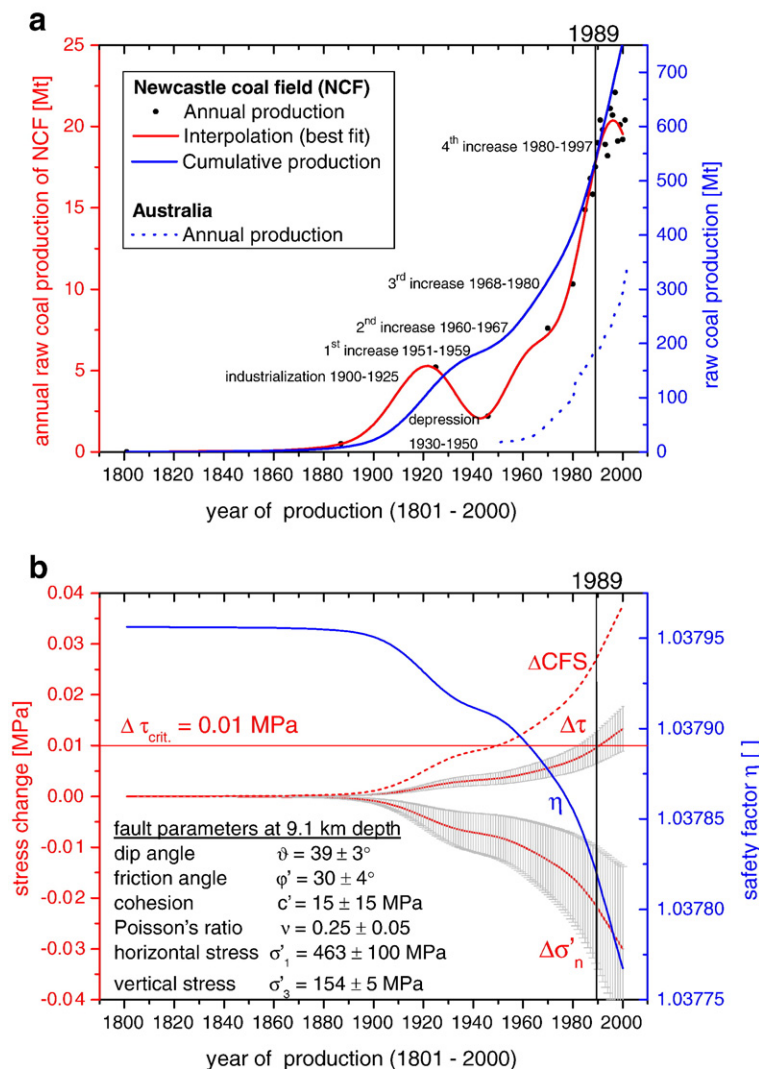


Fig. 2. Coal production and induced stress changes of the Newcastle coal field between 1801 and 2000. (a) Annual and cumulative raw coal production of the Newcastle coal field and Australia, (b) Evolution of the safety factor η , the Coulomb failure stress ΔCFS , the effective normal stress change $\Delta \sigma'_n$, and the shear stress change $\Delta \tau$ on the Newcastle fault exceeding $\Delta \tau_{crit}$ in the year 1991 ± 8 at a depth of 9.1 ± 0.5 km.

Table 1
Coal production data of the Newcastle coal field in 1989

Colliery name	Coal production (Mt)	
	Annual	Cum.
1 Endeavour	0.22 (1.3%)	6.73
2 Munmorah	1.15 (4.0%)	21.42
3 Wyee	0.67 (6.6%)	35.19
4 Chain Valley	0.26 (1.5%)	7.95
5 Moonee	1.45 (8.3%)	44.36
6 Wallarah	0.48 (2.7%)	14.69
7 Myuna	1.32 (7.5%)	40.39
8 Cooranbong	1.27 (7.2%)	38.86
9 Awaba	0.16 (0.9%)	4.89
10 Teralba	0.60 (3.4%)	18.36
11 Newstan	1.84 (10.5%)	56.30
12 Westside	0.71 (4.1%)	21.73
13 West Wallsend	3.41 (19.5%)	104.33
14 New Wallsend	1.25 (7.1%)	38.25
15 Southland	1.04 (5.9%)	31.82
16 Bloomfield	1.20 (6.8%)	36.71

(left) Names of the 16 main collieries (see Fig. 1). (middle) Absolute and relative annual coal production (in total: 17.52 Mt). (right) Cumulative (cum.) production since 1801 is 536.05 Mt, whereas the water discharge for each colliery is 144.20 Mt in 1989.

dewatered between 1801 and 2000. In the year 2000 it can be assumed that their maximum discharge, under steady-state conditions, resulted in a net withdrawal of up to 2438 ± 813 Mt. Steady-state conditions means that removed pore water above each colliery periodically was taken into consideration (net withdrawal in year 2000) versus the discharged water since 1801 (total withdrawal). Thus in year 1989, the water withdrawal of all 16 collieries (one colliery) was at least 2309 Mt (144 Mt). This value is based on a porosity of $7.5 \pm 2.5\%$ [19] of the dewatered Permian sediments above each colliery. The mass ratio $m_{water}/m_{coal} \leq 4.3$ is relatively small if compared to global statistics showing mass ratios of 1–150 between water and raw material [20].

2.3. Tectonophysical situation

The tectonophysical situation in the Newcastle–Hunter valley shows no evidence for Quaternary movements along its fault system [17]. Nevertheless, there is spatiotemporal evidence for at least four additional major earthquakes in the area near Newcastle: $M_L=4.9$ on January 27, 1841 [21]; $M_L=5.3$ on June 18, 1868 [21]; $M_S=5.3$ on December 18, 1925 [22], and $M_L=5.3$ on August 6, 1994 [23]. Over the last 150 to 200 years, this ongoing seismicity is interpreted as a reactivation of a pre-existing zone of weakness [24] inherent from the Permo-Triassic or Late Cretaceous tectonic evolution of the Sydney basin and the Australian passive margin [18].

Results indicate that this seismicity pattern is clustered and cyclic. It shows a quiescent period of more than 10,000 years followed by a short period of seismic activity lasting more than 150 years [18]. Moreover, the continental crust in Hunter Valley and eastern Australia is characterized by a high heat flow of 60 °C per kilometer crustal depth [25], which may explain the lithostatic stress concentrations in that region [26].

Determination of in-situ stress states is based on both tectonic field observations [16,17] and in-situ data in the Hunter Valley [27]. In-situ stress measurements of the vertical/gravitational principal stress component (S_v) and horizontal components (S_H , S_h) in up to 600 m depth indicate a current reverse fault regime with $(\sigma_1=S_H) > (\sigma_2=S_h) > (\sigma_3=S_v)$. $\sigma_{1,2,3}$ are the eigen-values of the lithostatic stress tensor σ . The in-situ measurements reveal a σ_1/σ_3 -ratio of 1.0–1.6 and tectonic field observations indicate higher values of 2.7–3.3, whereas average ratios of 2.2 are assumed to be more likely. Stress states in deeper depths can be determined by extrapolation, based on a linear regression model $S_H=rz$ with depth $z=[m]$ and regression coefficient $r=0.061 \pm 0.011 \text{ kg m}^{-3} \text{ m s}^{-2}$. At the mainshock's hypocentral depth of 11.5 km, the maximum principal stress would be $\sigma_1=702 \pm 127$ MPa, the minimum principal stress (gravitational stress) is $\sigma_3=311 \pm 5$ MPa, assuming a rock density of $2700 \pm 50 \text{ kg m}^{-3}$. Further, the S_H -stress orientation of 53° to Northeast [17] is in agreement with the principal horizontal stress direction of 44°, derived from the solution of reverse focal mechanism of the 1989 mainshock [13].

2.4. Geomechanical modeling

A three-dimensional lithostatic crust model was developed according to analytical solutions in elasticity theory for (1) stress changes below rectangular stripe unloads [28], (2) the elastic response of the crust [29], (3) the elastic response of fluid filled pores [30–32]), and (4) the in-situ stress parametrization. The crust model was applied to determine stress states beneath the Newcastle coal field ($60 \times 40 \times 30 \text{ km}^3$). Mass removals caused unloads L and negative vertical stress components $\Delta\sigma_L$ below the 16 collieries. Thus, vertical and horizontal lithostatic stresses were altered, due to the elastic response of the crust (Hook's law): $\Delta\sigma_3=\Delta\sigma_L$ and $\nu/1-\nu\Delta\sigma_L \leq \Delta\sigma_{1,2} < \Delta\sigma_L$ [33], where ν is the Poisson's ratio. It is more likely that $\Delta\sigma_{1,2} \geq \nu/(1-\nu)\Delta\sigma_L$, because horizontal principal strains $\epsilon_{1,2}$ are infinitesimal small and can be assumed to be $\epsilon_{1,2}=0$ in 10–15 km depth, where faults are generally locked [34,35]. As aforementioned, the fault

system in the Newcastle–Hunter Valley shows no evidence for Quaternary movements [18]. It was also suggested, that, e.g., the Hunter thrust fault is locked in depth [36]. Further, unloads also decreased the pore pressure. This was due to the elastic response of the fluid filled pores and discontinuities under undrained conditions [30–32]: $\Delta p_L = -B\Delta\bar{\sigma}$, where $\bar{\sigma}$ is the lithostatic mean stress and Skpton's coefficient B is taken as 0.8 [32].

Thus, the isotropic reduction of the pore pressures p increased the weight of the crust, which worked against the increase of the unload-induced anisotropic stresses $|\Delta\sigma_3| > |\Delta\sigma_2| = |\Delta\sigma_1|$ (transverse isotropic). Finally, the Newcastle fault was brought closer to failure by an increase in shear stress $\Delta\tau$ and a decrease in effective normal stress $\Delta\sigma'_n$ on the fault over a period of 188 years (Fig. 2b). The stability of a fault can be measured by a safety factor η , which describes the ratio between the Coulomb failure shear stress τ_f (the holding stress) and the Mohr shear stress τ (the driving stress):

$$\eta = \frac{\tau_f(c\varphi', \sigma'_n)}{\tau(\sigma_1, \sigma_3, \Delta\sigma_L\theta)} = \frac{c + (\tan\varphi')\sigma'_n}{\tau(\sigma_1, \sigma_3, \Delta\sigma_L\theta)},$$

where $\sigma'_n = \sigma_n - \alpha p$ is the effective normal stress perpendicular to the fault, $\alpha \approx 1$ is the Biot–Willis' coefficient [37], $c = 15 \pm 15$ MPa is the assumed cohesion and $\varphi' = 30 \pm 4^\circ$ is the assumed effective angle of friction within the fault. τ and σ'_n are functions of the fault dip angle $\theta = 39 \pm 3^\circ$, the principal components of the lithostatic stress σ_1 and σ_3 , and the hydrostatic pore pressure p . A fault is stable as long as $\eta > 1$. Using η as safety measure has two advantages. First, the dimensionless value can be compared with values of other earthquakes in different depths or tectonic regimes, and second, its statistical error $\delta\eta \leq |\eta|(\delta\tau_f/\tau_f + \delta\tau/|\tau|)$ (relative error summation) is much smaller when compared to other criteria, such as $\text{CFS} = \tau - \tau_f$, where $\delta\text{CFS} \leq \delta\tau + \delta\tau_f$ (absolute error summation).

3. Results and discussion

The shear safety η ranges between 0.8 and 1.2, indicating unstable pre-existing conditions, probably lasted over thousands of years. Simulation results show a continuous decrease of η from 1801 until 1989 (Fig. 2b). However, the reduction of 0.01% due to unloading is infinitesimally small if compared to the statistical variability of 20% resulting mainly from the in-situ stress and from the geomechanical properties of the fault. The decrease of the fault's shear safety in a highly stressed but seismologically stable continental

crust is one indication that the Newcastle reverse fault came closer to failure.

Another indication for the potential of earthquake triggering are the induced shear stress increase $\Delta\tau$ and effective normal stress decrease $\Delta\sigma'_n$ on the Newcastle fault (Fig. 2b). Between 1801 and 1945, induced stresses ($\Delta\tau < 0.003$ MPa and $\Delta\sigma'_n > -0.009$ MPa) were negligible at hypocentral depth of the Newcastle fault (11.5 ± 1.5 km). But, the fault stress that brought it closer to failure, had been accelerating especially since the 1960's. A circular shaped stress concentration (stress nucleus) of a minimum critical shear stress change $\Delta\tau_{\text{crit}} = 0.01$ MPa (0.1 bar) reached the Newcastle fault at a depth of 7–11 km in the year 1991 ± 8 (Figs. 3 and 2b). $\Delta\tau_{\text{crit}}$, which is the minimum Coulomb failure stress ΔCFS , is generally observed to be necessary for triggering earthquakes [38,9,39]. Estimates depend on the fault properties including their statistical uncertainties, while causing a temporal error of ± 8 years.

In 1989, the year of the earthquake, a $\Delta\tau_{\text{crit}}$ -nucleus was centered on the fault at 9.1 ± 0.5 km depth (Fig. 3). Hypothetically, taking 9.1 km as nucleation point, the depth of the hypocenter (11.5 ± 1.5 km) could have been over-estimated up to 45% by the regional seismic network [14]. This result is in agreement with over-estimations of hypocentral depths of $88 \pm 30\%$ for shallow earthquakes in seismological stable continental regions, such as Australia, where instrumental coverage (seismic networks) is sparse [40].

Further, the determination of the stressed area on the fault with a radius of $r_{\text{crit}} = 2014 \pm 107$ m made it possible

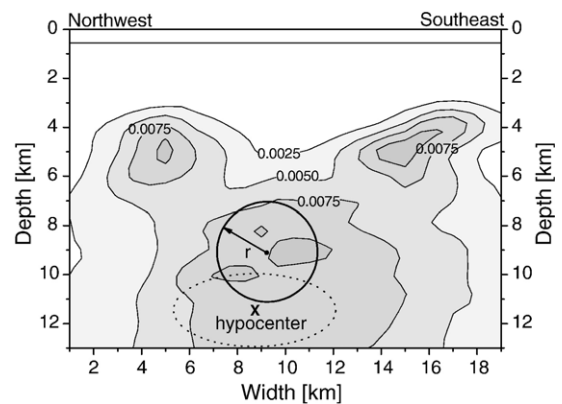


Fig. 3. Distribution of the shear stress change $\Delta\tau = [\text{MPa}]$ on the 39° dipping Newcastle fault in 1989. $\Delta\tau_{\text{crit}}$ -isobars affected a circular area (stress nucleus) of radius $r_{\text{crit}} = 2014 \pm 107$ m. Geometrically, the circle center is the mean value of the three centers of the τ_{crit} -clusters. If the Newcastle fault extends into shallower depths (< 6 km) other stress nuclei would occur. This may explain, why the 1994 $M_L = 5.3$ Ellalong earthquake ruptured at 1.4 km depth on another fault in the vicinity of the Southland/Ellalong colliery (see Fig. 1 and Table 1).

to estimate a potential seismic moment of $M_0 = 1.77 \pm 0.89 \times 10^{17}$ Nm (Fig. 3), which is equivalent to a seismic moment magnitude of $M_w = 5.4^{+0.2}_{-0.3}$. These estimates are based on the moment-scaling law $M_0 = 16/7 \Delta\sigma r^3$ and the moment-magnitude relation $M_w = (\log M_0 - 9.1)/1.5$, examining a stress drop of $\Delta\sigma = 9.5 \pm 3.2$ MPa and a rupture radius r . The rupture radius is assumed to be equal to the stress radius r_{crit} . The $\Delta\sigma$ -value is typical for Australian earthquakes and is based on the 1968 Meckering earthquake and the 1988 Tennant Creek earthquakes. Independently, a stress drop ranging between 2.4 and 9.9 MPa was estimated after the Newcastle earthquake [15].

In comparison, McGarr's mass-moment relationship $M_0 = 2\mu\Delta mh/\rho$ [41] determines a seismic moment of $1.71 \pm 0.24 \times 10^{19}$ Nm ($M_w = 6.8 \pm 0.1$), which is 55 times larger than the moment of the 1989 mainshock. The estimation of M_0 is based on a rigidity $\mu = 30000 \pm 5000$ MPa, a mass change Δm , and a seismogenic part $h = 98.5 \pm 0.5\%$ of the 32.5 ± 2.5 km thick crust with a density $\rho = 2700 \pm 50$ kg m⁻³. The mass removal of 778 Mt (water and 37.5% of the total coal production between 1801 and 1989) results from the four closest collieries (West Wallsend, Teralba, Newstan and Westside), which mainly altered the crustal in-situ stress near the Newcastle fault (Fig. 1 and Table 1).

4. Conclusion

The size of the area (volume) in the Newcastle coal field that was affected by (critical) shear stress changes (Fig. 1) was larger than the ruptured area of the Newcastle fault (13 km²). It can be anticipated that other faults could be also critically stressed in that region (Fig. 1). It may explain why, for example, the 1925 earth quake ruptured potentially on another shallower fault in the area of highest stress alterations. It could also explain that the seismic moment magnitude of the 1989 Newcastle earthquake is associated with only a fraction of the mass removal (1 of 55), based on McGarr's mass-moment relationship. Finally, the geomechanical modeling results suggest a significant spatiotemporal correlative between crustal mass alterations and the 1989 Newcastle earthquake. Moreover, the results indicate that mass removals at the sub/surface, which have occurred since the beginning of mining activities in year 1801, did indeed bring the Newcastle fault closer to failure — in a depth where the 1989 M5.6 Newcastle nucleated. This conclusion confirms other observations of an ongoing seismicity in the Newcastle region since the beginning of the 19th century after a dormant period of 10,000 years of no seismicity.

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