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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.

Keywords: rock mechanics; geomechanics; earthquake mechanics; earthquake prediction; mining; human-natural coupled system

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 Völkershausen 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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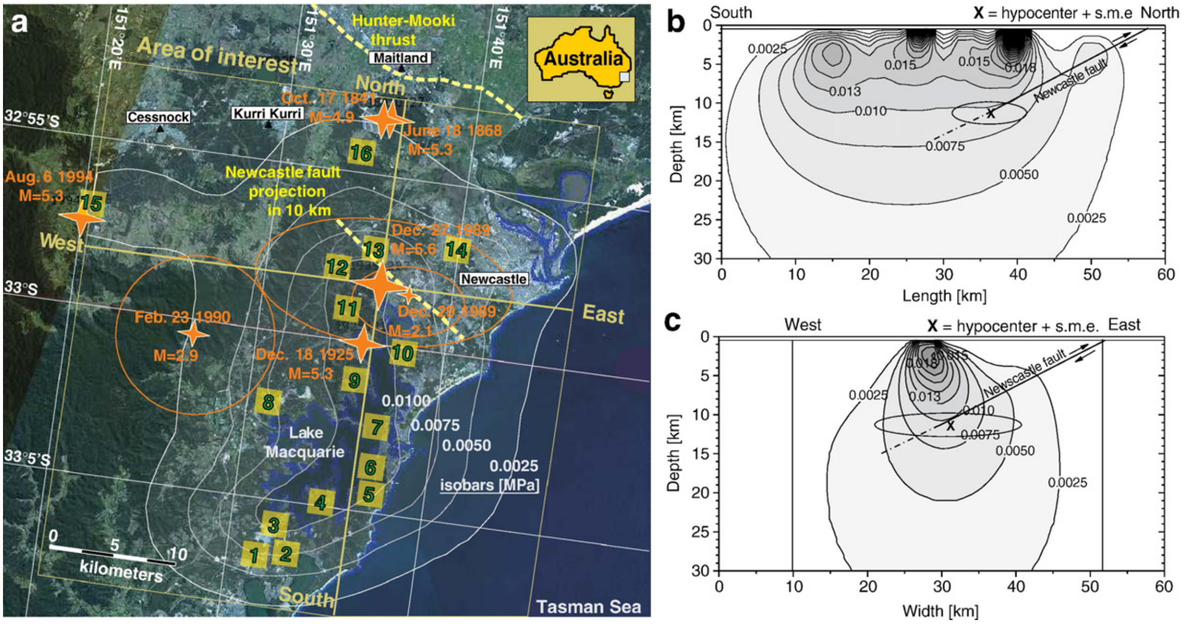

Fig. 1. Newcastle and the Newcastle coal field: (a) Satellite image of the area of interest near Newcastle* with 16 collieries of the Newcastle coal field (squares); epicenter±error of the Newcastle mainshock on December 27, 1989 (big diamond), the two aftershocks on December 29, 1989 and February 23, 1990 (small diamonds) and other earthquakes (medium diamonds); orientation of the Newcastle fault at 10 depth striking to 330±10° Northwest with a dip angle of 39±3°; 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 Sate [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° 36′ 25″ East and latitude 32° 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±10° (mean±s.m.e) to Northwest with a dip angle of 39±3° (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].