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TECHNICAL ARTICLE

Mine Water Discharge and Flooding: A Cause of Severe Earthquakes

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Abstract Severe earthquakes can be triggered by dewatering and flooding of mines, as these activities alter the loading of the Earth's crust and tectonic stresses in its interior. Worldwide, more than 200 studies have noted sites where human-induced stresses could have reactivated preexisting faults, triggering earthquakes with seismic moment magnitudes of up to $M = 7$ on the Richter scale. This can only occur where faults are already under high tectonic stresses that have built up over many years. Stable continental regions are seismically less active than unstable regions (e.g. California, Japan, and Turkey). Consequently, faults in stable continental regions can be more earthquake-trigger sensitive, since accumulated stresses have not reached failure conditions. This paper provides an overview of officially recognized mining-triggered earthquakes with magnitudes $M \geq 5.0$. The article illuminates that these earthquakes can cause serious socio-economic losses with negative implications for the long-term sustainable development of countries abundant in natural resources and of mining regions, in particular. Historic data suggest that regional geological conditions (e.g. structural geology and tectonic in-situ stress states) are more important in forecasting the potential of earthquake triggering than the scale of the mining activities. Overall, such forecasts should be made to estimate and mitigate potential socio-economic earthquake risks associated with geoengineering operations of extractive industries such as mining.

Keywords Earthquake hazards · Environmental change · Extractive industries · Flooding · Mine water discharge · Mining triggered earthquakes · Natural resources · Risks · Sustainable development · Water exploitation

Introduction

One of the first documented earthquakes associated with mining occurred in the year 1552, near the city of Annaberg (southern Germany). This was a center of one of Europe's major ore mining regions between the fifteenth and eighteenth centuries (Lehmann 1699). In 1908, a seismological station was installed to continuously monitor earthquakes being caused by mining in the city of Bochum, in Germany's Ruhr coal mining region (Mintrop 1947). Since then, many earthquakes officially attributed to mining activities worldwide have been instrumentally recorded and analyzed. Examples include the deep gold mines of South Africa (e.g. McGarr et al. 1975; Richardson and Jordan 2002), the black coal districts in Australia and Asia (e.g. Klose 2007a; Zhang et al. 1996), ore deposits in eastern Europe (e.g. Kremenetskaya and Trjapitsin 1995; Kwiatek 2004; Malovichko et al. 2005), coal mining areas in West Europe (e.g. Driad-Lebeau et al. 2005; Grünthal and Minkley 2006; Redmayne 1988), and several mining areas in North America (e.g. Arabasz and Pechmann 2001; Hasegawa et al. 1989; Long and Copeland 1989; Pechmann et al. 1995; Pomeroy et al. 1976). For example, 10–25% of the earthquakes recorded by the UK regional seismic network of the British Geological Survey are induced or triggered by coal mining activities (Donnelly 2006; Redmayne 1988).

This article provides an overview of major mining-triggered earthquakes, which can have serious socio-economic

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implications. Mining-triggered seismicity differs from mining-induced seismicity; the components that determine the hazards and risks of mining-triggered earthquakes are discussed, along with the physical mechanisms that can trigger earthquakes, and how dewatering and flooding of mines, in particular, can alter tectonic stresses and increase the likelihood of earthquakes on pre-existing faults.

A Definition of Mining-Triggered Earthquakes

Several research studies indicate that there are characteristic differences between seismicity that is induced or triggered by mining operations (McGarr et al. 2002). Mining-induced earthquakes have small seismic moment magnitudes of approximately $M \ll 4.5$ on the Richter scale (e.g. Melnikov et al. 1996; Richardson and Jordan 2002; Young et al. 1989; Zhang et al. 1996). They only occur in the vicinity ($\ll$1 km) of underground excavations, due to larger stress redistributions (>1%) of the tectonic in situ stress (Brady and Brown 1993; Cook 1976; Gibowicz and Kijko 1994). In contrast, mining-triggered earthquakes rupture on preexisting faults, often relatively far from underground excavations (0–30 km). These seismic events would occur under natural conditions if tectonic stress states changed, e.g. at plate boundaries, rift systems or regions of volcanic activity. But, they can also result from the elastostatic response of the continental crust due to very small induced stress changes ($\ll$1%) associated with perturbations at the subsurface:

- Mass removal or mass accumulation, including movement of water,
- Fluid pressure changes with/without fluid flow in rock fractures/pores (e.g. dewatering and flooding),
- Volumetric changes (e.g. contraction of underground excavations),
- Thermal changes (e.g. temperature gradients around underground excavations).

Up till 2005, these earthquakes accounted for 56% (Fig. 1) of all worldwide documented human-triggered earthquakes with seismic moment magnitudes $M > 4.5$ on the Richter scale. This global environmental change has increased worldwide and exponentially over time (Fig. 2).

Statistics also indicate that mining-triggered earthquakes occur mostly in stable continental regions (>75%) of very low natural seismicity (<5%, aseismic) that tend to be very shallow and bimodally distributed at 0–10 and 20–30 km depth (Klose and Seeber 2007). Natural tectonic conditions in these regions are stable over very long periods (e.g. millennia), compared to active continental regions with very high natural seismicity (>95%) such as California, Japan, or Turkey (Klose 2006a). In other words, mining

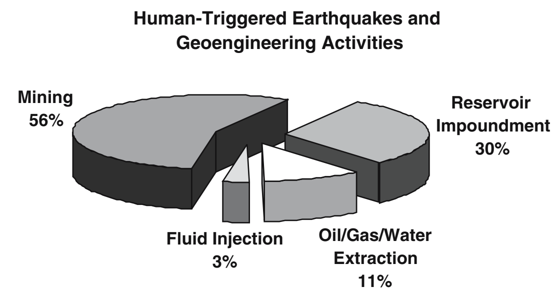

Fig. 1 Human-triggered earthquakes per geoengineering activity; the data are based on the global catalog of human-triggered earthquakes in 2005 (Klose 2006a)

activities can alter stresses in the interior of the Earth's crust at levels that bring pre-existing faults to failure. This phenomenon is called geomechanical pollution (Klose 2006b; Seeber 2002). However, the low rate of human-triggered seismicity in seismically active continental regions (<25%) might be due to the fact that less attention is paid to seismic events caused by humans and that most earthquakes are assumed to be of tectonic origin.

Hazards and Risks of Mining-triggered Earthquakes

Overall, two factors determine the potential of mining-triggered earthquake hazard in the vicinity of geoengineering activities:

- Conditions of the natural system (Earth's crust) and
- Conditions of the human system (e.g. extractive industry operations).

Geological and tectonic conditions (natural system) primarily determine the potential of triggering a severe earthquake. For example, natural tectonic stresses can build up in stable continental regions (e.g. Australia, and many parts of America, Africa, Europe, and Asia) over long periods of time and initiate faults close to failure without overcoming the strength of the rock in the faults. Thus, faults can be particularly earthquake trigger-sensitive in stable continental regions (Townend and Zoback 2000) or in some sub-regions with high stress concentrations (Hough et al. 2003).

The scale and impact of human activities determine how rapidly the potential of earthquake hazard changes (Klose 2007a; Simpson 1986). In the case of the 1989 M5.6 Newcastle earthquake in Australia, coal mining (and its associated dewatering) caused unloading and lithostatic stress alterations beneath the Newcastle coal field over the course of 200-years (discussed in more detail below). These induced stresses were very small but they were apparently high enough to bring the Newcastle fault to

Table 1 Officially recognized mining-triggered earthquakes with local magnitudes $M_{local} \geq 5.0$ on the Richter scale that are documented based on physical evidence (e.g. geomechanical calculations) and/or spatial and temporal evidence (correlations)

Location	Earthquake mm/dd/yyyy	Magnitude M_{local}	Intensity I_0	Damage Mill. US $	Fatalities	Mining	Evidence for triggering	
							Physical	Space/time
Provadia, Bulgaria[a]	06/12/1986	5.7	VIII	–	3[k]	Potash	no	yes
Newcastle, Australia[b]	12/27/1989	5.6	VIII	5000	13	Coal	yes	yes
Völkershausen, Germany[c]	03/13/1989	5.6	VIII-IX	76	0	Potash	yes	yes
Ellalong, Australia[b]	08/06/1994	5.4	VII	52	0	Coal	yes	yes
Klerksdorp, S. Africa[d]	03/09/2005	5.3	VIII	21[k]	2[k]	Gold	no	yes
Boolaroo, Australia[b]	12/18/1925	5.3	VI	–	0	Coal	yes	yes
Maitland, Australia[b]	06/18/1868	5.3	VI	–	0	Coal	yes	yes
Sünna, Germany[e]	06/23/1975	5.2	VIII	–	–	Potash	no	yes
Welkom, S. Africa[f]	12/08/1976	5.2	VII	–	–	Gold	no	yes
Klerksdorp, S. Africa[f]	04/07/1977	5.2	VII	–	–	Gold	no	yes
Trona, USA[g]	02/03/1995	5.2	V	–	1	Potash	no	yes
Welkom, S. Africa[h]	04/22/1999	5.1	–	–	2[d]	Gold	no	yes
Heringen, Germany[i]	02/22/1953	5.0	VIII	–	–	Potash	no	yes
Lubin, Poland[j]	03/24/1977	5.0	–	–	–	Copper	no	yes
Klerksdorp, S. Africa[h]	01/28/1984	5.0	–	–	–	Gold	no	yes
Hartebeesfontein, S. Africa[h]	08/21/1997	5.0	–	–	>15[d]	Gold	no	yes
Klerksdorp, S. Africa[h]	07/31/2001	5.0	–	–	–	Gold	no	yes

Intensities, I_0, of these seismic events caused minor to major damages. Economic costs are discounted to the year of the earthquake. Data of financial damages are inflation adjusted and compounded to year 2007 for comparison reasons

[a] Knoll et al. 1996; [b] Klose 2007a; [c] Knoll 1990; [d] USGS earthquake catalog http://earthquake.usgs.gov/eqcenter/eqarchives/significant; [e] Grünthal and Minkley 2006; [f] McGarr et al. 1989; [g] Pechmann et al. 1995; [h] Schulte and Mooney 2005; [i] Sponheuer et al. 1960; [j] Gibowicz 1985; [k] EM-DAT the international disaster database http://www.em-dat.net/

failure, triggering an earthquake of magnitude 5.6 on the Richter scale with a rupture radius of approximately 2 km (Klose 2007a). Many other examples of naturally triggered and human-triggered earthquakes have been associated with relatively small critical shear stress changes in faults ranging between 0.001 and 0.01 megapascals (10^6 Pa) (Cochran et al. 2004; Evans 1989; Seeber et al. 1998; Talwani 1976).

Earthquake risk is the most important component that needs to be determined in order to keep global mining operations and their surrounding region on a long-term sustainable path of development. Theoretically, risk is determined by: (a) the hazard of a potentially threatening event (e.g. macroseismic intensities or ground motion of an earthquake) and (b) the vulnerability of the exposed elements (e.g. urban areas, human individuals). Based on this definition, risk can be estimated as follows:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Exposure} \times \text{Elements}$$

or

$$\text{Risk} = \mathit{argmin}\,[\mu(\text{Hazard}), \mu(\text{Vulnerability})] \times \text{Exposure} \times \text{Elements},$$

where *arg min*-operator describes the possibility of risk as the minimum value of the logic argument "hazard and vulnerability", with μ as membership functions (Klose 2007b; UNDRO 1980).

Earthquake risks (potential losses) increase with time when extractive industry operations (e.g. mining) occur near industrialized or urbanized areas because these triggered earthquakes do not occur randomly. They are spatially and temporally related to the physical impact of the operations, i.e. stress alterations in the rock mass. Hence, mining-triggered earthquake risks can be deterministically determined or forecasted in space and time but they cannot be predicted due to the lack of information about the interior of the crust. For example, fault orientations can be estimated based on geological observations in the vicinity of the mining area, but specific earthquake nucleation points can be only simulated with high uncertainties that cause high temporal prediction errors (e.g. <10 years), unless fault locations are known (Klose 2007a).

Socio-economic risks of mining-triggered earthquakes can be very high. The 1989 Newcastle earthquake in Australia was a very costly earthquake (Klose 2006c), as documented by spatial, temporal, and geomechanical evidence (Fig. 3 and Table 1). The event caused 13 deaths and

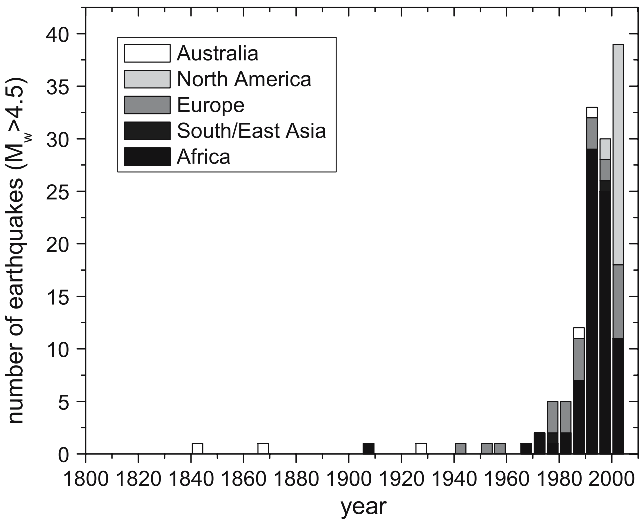

Fig. 2 Mining-triggered earthquakes per continent and time; the data are based on the global catalog of human-triggered earthquakes in 2005 (Klose 2006a)

damages estimated at $3.5 billion (US, 1989 value), which was 3.4% of Australia's 1989 national income (GDI) (source: Australian Bureau of Statistics). Furthermore, the financial loss accounted for 60% of the Australian GDI growth and 80% of the GDI per capita growth between 1988 and 1989. It also accounted for 13% of the total costs of all natural disasters and 94% of the costs of all earthquakes recorded in Australia from 1967 to 1999 (BTE 2001). This result suggests that mining-triggered earthquakes can have serious impacts not only on the mining region but also on a Nation's income and could possibly contribute to the observation that countries abundant in natural resources tend to grow slower than those without substantial natural resources (Sachs and Warner 1999).

A comparison to other earthquakes of tectonic origin shows that mining-triggered earthquakes can be as destructive as tectonic earthquakes of similar magnitude. The 1994 M6.6 Northridge earthquake killed 60 people and caused a financial damage of $21.3 billion (US) (source: EM-DAT, the International Disaster Database; inflation adjusted and compounded to year 2007). The 1992 M7.4 Landers earthquake killed 3 people and caused $1.2 billion (US) in financial damages, or 1/4 of the damage of the 1989 Newcastle earthquake (Table 1).

Earthquake Triggering due to Mine Water Discharge and Flooding

Overall, a compilation of mining-triggered earthquakes underscores an exponential global increase in seismicity (Fig. 2). Although one might suspect that this is due to the worldwide increase of instrumental coverage of seismicity, this is not likely to be a major contributing factor since earthquakes with seismic magnitudes $M > 4.5$ can be recognized without instrumental recording. Increases in mining productivity (mass raw material per year), mining area (horizontal length scale), and mining depth (vertical length scale) all likely contribute.

The last of these has an additional effect; mine water is pumped to the surface and discharged, particularly in deep mines. Such volume/mass changes at the Earth's surface can trigger earthquakes. First of all, the weight γ generally increases with increased mining depth z, whereas γ remains constant despite the size of the mining area A of this mined rock mass body (Fig. 4). Second, the total weight of the removed raw material and mine water causes an unload σ_v (Earth pressure) beneath the lowermost part of the mined body. On top of this, mass removals (dewatering strata) and mass accumulations (flooding) due to mine operations at the sub/surface (0–3 km) can perturb tectonic stresses in the mines' near- and far-field (0–30 km). Such crustal mass variations change the gravitational principal stress (vertical). Horizontal principal stress components change by approximately 1/3 to 1/2 of the vertical un/load due to the elastostatic response of the crust (Klose 2007a). Tectonic stresses in a reverse fault regime, for example, that alter due to unloading bring a shallow dipping fault (<45°) closer to failure (Fig. 5). Reverse faults form under high horizontal and low vertical tectonic stresses.

To illustrate how this occurs, let us examine the mining that has taken place in the Newcastle coal field of SE Australia. The area has been dewatered since 1801 to make underground mining possible and to keep the coal seals dry. The active collieries are mined at an average depth of 325 ± 175 m. Since the second half of the twentieth century, they laterally extend 2.5 by 2.5 km^2 and more, due to the length of longwall cutters. In the year 2000, the amount of water pumped totaled up to 3.25 gigatonnes (10^9 t) for the 16 collieries within the coal field (Figs. 6, 7). The mass ratio between water and coal was ≤4.3, which is relatively small compared to global statistics that show mass ratios of water to raw material ranging between 1 and 150 (Fernandez-Rubio and Fernandez-Loca 1993).

Newcastle is situated at the NE boundary of the Sydney Basin, a continental region that was seismically inactive during the Quaternary (>10,000 years), before mining began in 1799 (Chaytor and Huftile 2000; Klose 2007a). Geological and tectonophysical analyses of the continental crust near Newcastle shows a reverse fault regime that is associated with an up to three times higher horizontal lithostatic stress component than the minimal vertical stress component. Moreover, the Newcastle fault zone beneath the coal field where the 1989 Newcastle earthquake nucleated was shallow and dipped 39 ± 3° to the

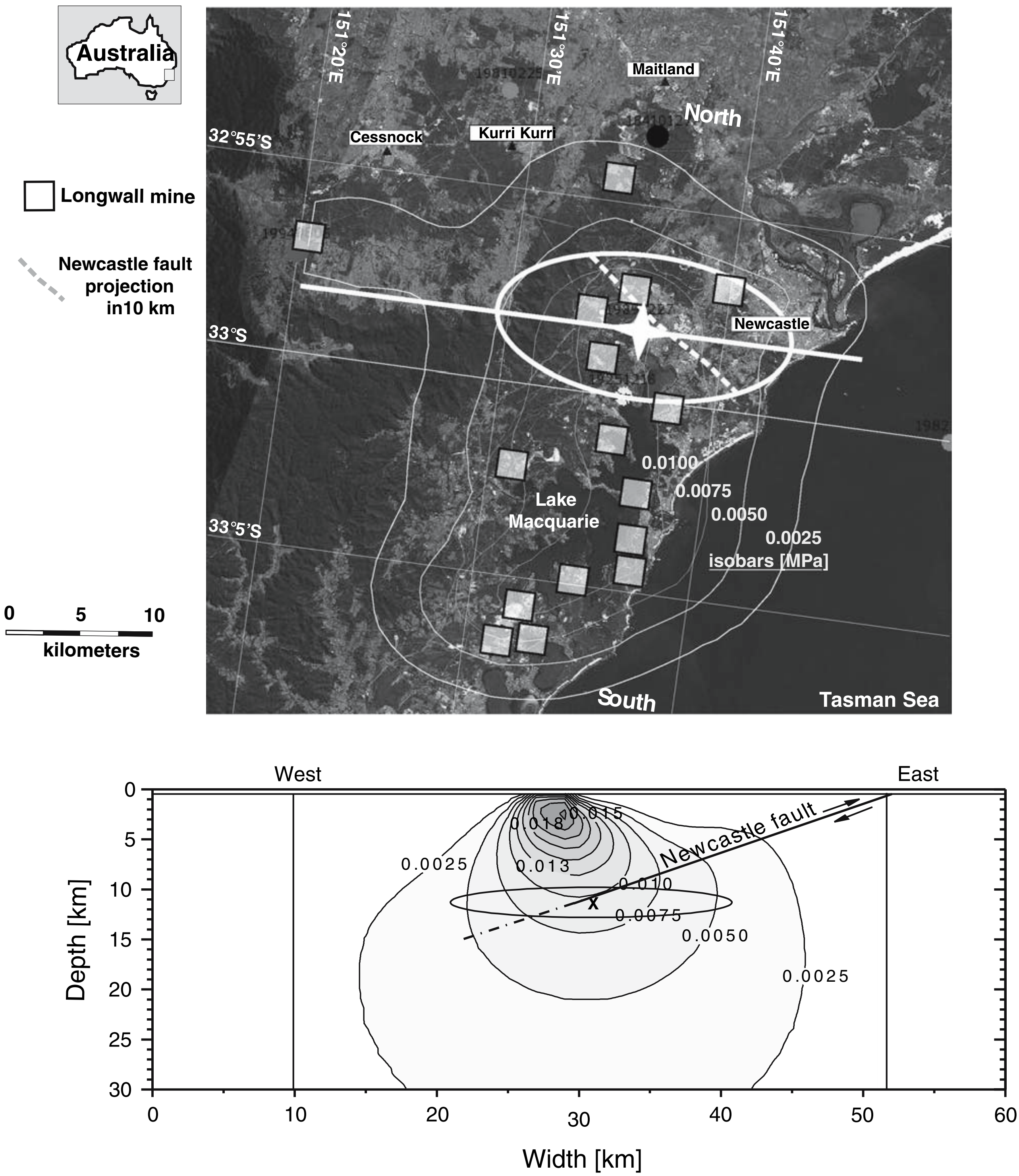

Fig. 3 Deep coal mines of the Newcastle coal field in South-East Australia and the distribution the tectonic stress changes in year 1989 due to mass-induced unloads beneath the mines. The hypocenter of the 1989 M5.6 Newcastle earthquake was in 11.5 ± 1.5 km depth (see *large ellipse*) and determined from a regional seismic network (Gibson et al. 1990). The stress distributions are shown for shear stress changes (in MPa) on the 39° dipping volume elements (orientation of the Newcastle fault) in 10 km depth and along the East–West cross section

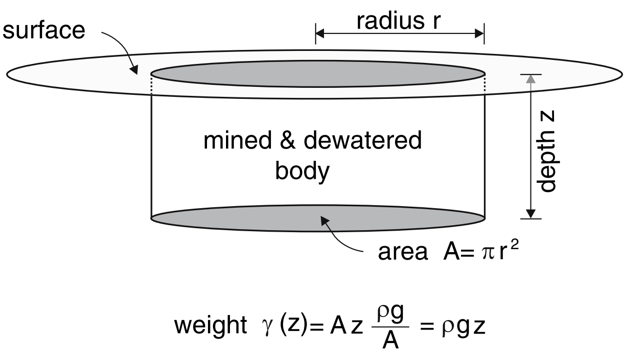

Fig. 4 Effect of changing weight of the Earth's crust as a function of mining depth, g or g(z) is the gravitational acceleration. The mined rock mass body is assumed to have a cylindrical shape to keep calculations simple

Southwest (Fig. 3). The fault was stressed due to the dewatering of the deep mines 10 km above (Klose 2007a).

The driving force that can trigger shear slip on a preexisting fault is an increasing shear stress parallel to it and/or a decreasing effective normal stress that is perpendicular to it (Fig. 5). Failures occur when induced shear stresses (the driving force) exceed the failure stresses (the holding force) or the strength of the rock mass discontinuity. The geomechanical modeling of the nucleation process of the 1989 Newcastle earthquake illustrates that shear stress changes should have peaked and effective normal stress should have been at a minimum on the Newcastle fault, at a depth of up to 9.1 ± 0.5 km in 1991 ± 8 years, after 188 years of permanent mass reductions of the crust. This result confirmed seismological observations that estimated the epicenter of the earthquake at a depth of 10–13 km (Gibson et al. 1990). The lithostatic model indicated that the induced shear stresses at that time reached critical levels of 0.01 MPa (10 kPa, 0.1 bar) within a 13 km^2 large area of the Newcastle fault at that depth (Klose 2007a). This quantitative evidence suggests that mining-induced stresses can most likely reactivate pre-existing faults. The Newcastle fault was probably reactivated in 1989, triggering an earthquake beneath the coal field that exhibited a seismic moment magnitude of 5.6 on the Richter scale.

Conclusions

More than 200 human-triggered earthquakes, with seismic moment magnitudes ranging between 4.5 and 7.3 on the Richter scale, have been documented. Those earthquakes are associated with mining, water reservoir impoundment, oil/gas production, and fluid injection. The data suggest that more than half of these are associated with mining operations and that these have had serious socio-economic implications for entire mining regions and national income. Historical data specifically show that such earthquakes are

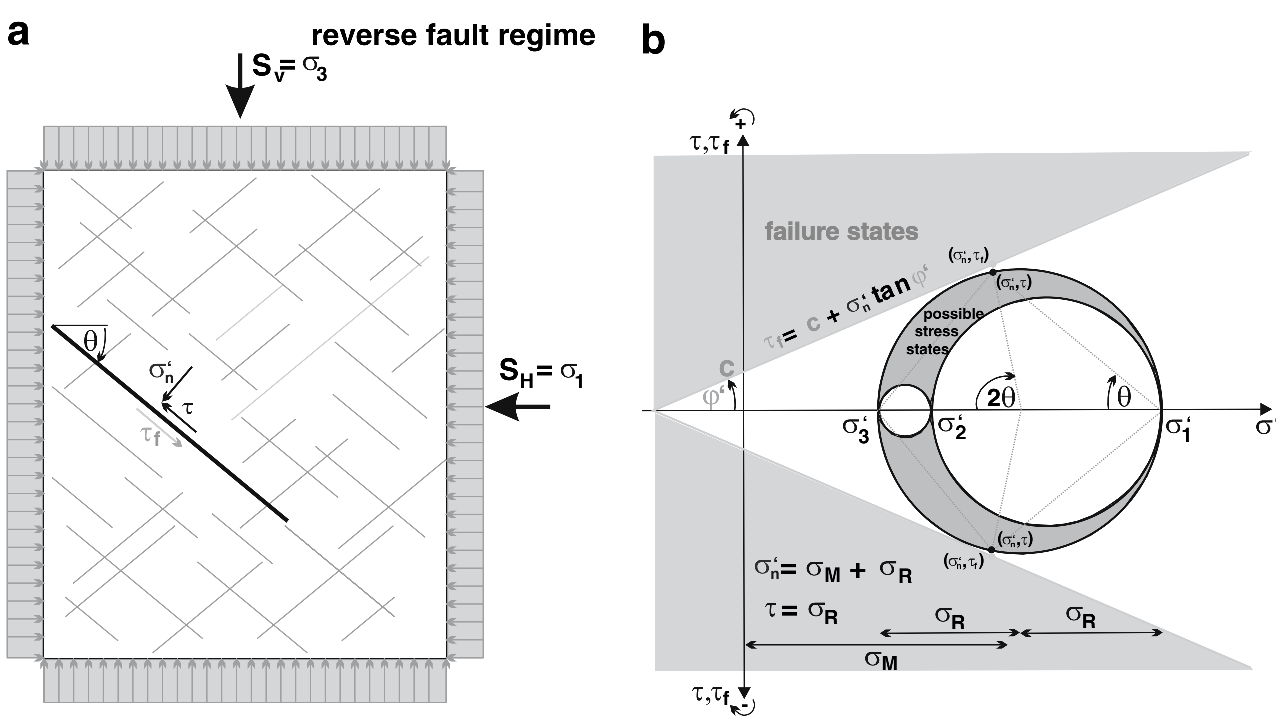

Fig. 5 Rock mass discontinuity, e.g. fault (**a**), and its tectonic stress states $\sigma_1 > \sigma_3$ (tectonic reverse fault regime) (**b**). Tectonic stresses can be altered (driving forces for failure: shear stress τ and normal stress σ_n). Failure shear stresses (holding forces: τ_f) on a fault are described by the Coulomb failure condition

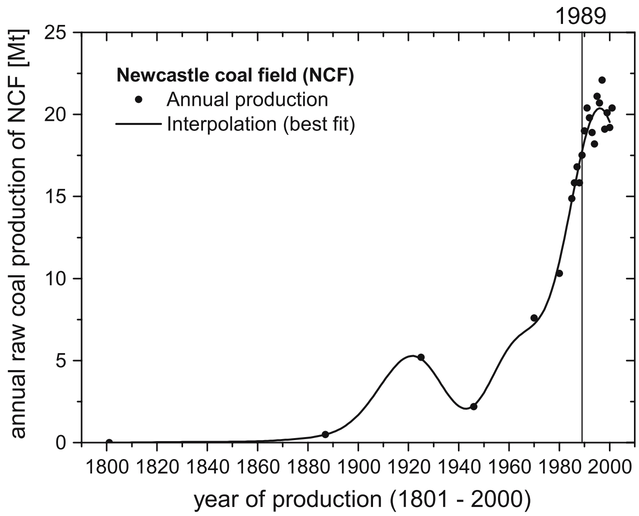

Fig. 6 Coal production of all 16 coal mines within the Newcastle coal field in New South Wales (Australia). The best fit of the production data is based on a Gaussian process model (Klose 2007a)

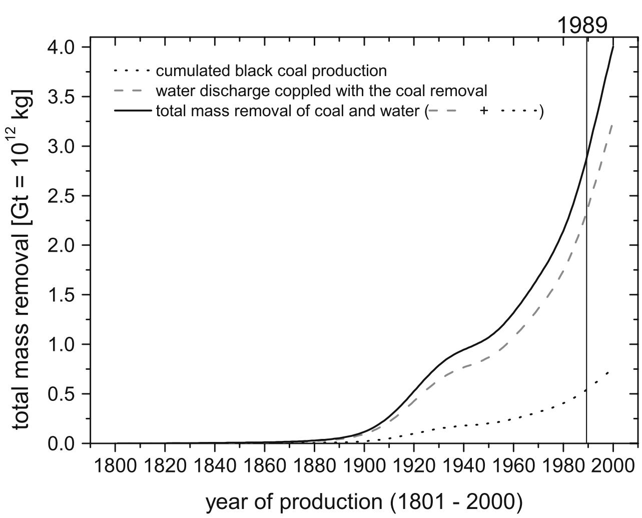

Fig. 7 Comparison between the cumulative coal production and the water discharge in the Newcastle coal field

associated with loading and unloading of the continental crust, caused by dewatering and flooding of mines, in many mining regions worldwide. The potential of triggering earthquakes by mining is determined by geological conditions, specifically: pre-existing fault zones that favor shear failure, and pre-existing tectonic stress that bring faults close to failure without overcoming the strength of the rock.

For example, the 1989 M5.6 Newcastle earthquake in Australia and the 1989 M5.6 Völkershausen earthquake in Germany were two instances where spatial and temporal correlations and comprehensive geomechanical evidences link mining activities and seismic events. Interestingly, there are other cases where a geomechanical modeling of the elastostatic behavior of the Earth's crust may be applied to better understand the interlinkage between mining, seismicity, and sustainable development. For instance, major coal and ore mining regions in China may be the cause of observed seismic events beneath deep mines that have been active since the end of the nineteenth century (Matsunami et al. 2003; Wang and Li 1987; Wright 1981).

The data outlined in this article suggest that geomechanical calculation in combination with earthquake hazard and risk maps should be developed for large-scale mining projects. Spatial and temporal data of earthquake hazards, vulnerabilities, and risks can be simulated to determine risk hotspots in the vicinity of mining operations. Risk or safety maps (Safety = Risk − 1) could help to mitigate or reduce socio-economic damages caused by extractive industry operations such as mining. For example, ground motion data could be simulated, based on mechanically determined earthquake source distances and seismic moments of potentially rupturing faults (e.g. Boore 2003). Seismic moments could be assessed due to the mass-moment relationship (McGarr 1976) or stress–moment relationship (Klose 2007a).

In conclusion, socio-economic earthquake damages associated with mining have increased exponentially over the course of the twentieth century due to the increasing number, size, and productivity of geoengineering activities of extractive industries (in average every decade by a factor of 2). Geological analyses of the tectonic conditions of the Earth's crust can be used to determine the potential of earthquake triggering in the vicinity of geoengineering activities; where the potential of triggering earthquakes appears to be significant. Mitigating or risk avoidance strategies may be appropriate in order to keep the balance between the needs of wealth growth, socio-economic and environmental sustainability, and aesthetic integrity of the nature.

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