Coincidence of Mines and Earthquakes in Australia

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Abstract: The continent of Australia is wholly intraplate and has one of the world's highest rates of intraplate seismicity – there is evidence that much of this seismic activity is associated with mining activity. Significant earthquakes have occurred near operating or historic mine sites throughout Australia, and there are numerous reports from other countries of earthquakes induced or triggered by mining. Using the criterion that earthquakes more than 30 km from mines were "natural" as distinguished from the earthquakes induced by & near mines, Ortlepp (2005) determined that 98% of the earthquakes, magnitudes 3.5–4.0 (M_L), recorded in 50 years in the Kaap-Vaal craton of South Africa were associated with mines. Ortlepp's 30-km criterion is applied to the Australian earthquake and mine catalogues to make a preliminary survey of the geographical, i.e., spatial, association of these two phenomena. The data consist of 2,259 earthquakes from the "Australian region" in the magnitude range, $3.5 \leq M \leq 7.3$, during the period 1800-2011; 1,273 "historic" mines; and, 359 "operating" mines (Geoscience Australia 2011). The resulting map of Australia employs a colour code to display the proximity of earthquakes to mines: green earthquakes and blue mines are earthquake-mine pairs separated by >30 km, and the red-red earthquake-mine pairs are separated by ≤30 km.. The map exhibits a regional diversity: the green earthquakes and blue mines are fairly well dispersed across the continent, but many red-red earthquake-mine pairs often occur together in restricted patches of intense activity. Independent evidence suggests that both the M6.3–M6.7 (3 events) 1988 Tennant Creek earthquake sequence and the M5.1 2010 Kalgoorlie earthquake are related to the historic & continuing, intensive hard-rock gold mining at these sites. Sydney is ringed with red patches that trace the outcrop of the Illawara Coal Measures, and isolated red patches extend to northern Queensland and to southern Victoria. There is a red patch in the old hardrock mining region of northwestern Tasmania and a mixture of red&green seismicity in the Flinders Ranges & Adelaide Hills, SA. The red patches represent concentrations of geographically coincident earthquake-mine pairs that would not be expected from the correlation of two independent, i.e., un-correlated, populations of mines & earthquakes. This suggests that these earthquakes are *minequakes* – that there is some necessary reciprocal connection between the two phenomena – either that the mines cause earthquakes in the sense that the earthquakes would have had a low probability of occurring had the mines not been dug; or that, on a geologic time scale, the earthquakes had caused the mines by uplifting the topography by thrust faulting, thereby exposing ore as outcrop to be mined; or, both. Mining causes a significant fraction of Australian seismicity – recognizing this is a necessary step to separating "natural" seismic events from all the others.

Keywords: mine, earthquake, Australia, intraplate, induced, triggered, seismicity, Tennant Creek, Kalgoorlie, Olympic Dam

Introduction: The continent of Australia is wholly *intraplate* and has one of the world's highest rates of *intraplate* seismicity (McCue et al. 2008) – there is evidence that much of this seismic activity is associated with mining activity (Cranswick 2011).

For example, the 22 January 1988 Tennant Creek Earthquakes sequence, consisting of three of Australia's largest earthquakes, magnitudes 6.3, 6.4, and 6.7, within a 12-hour period, created two fault scarps with a maximum height of 1.8 m and combined length of 32 km (McCue 1990) and excited the interest of seismologists worldwide – hundreds of scientific papers refer to it (Google Scholar Search 2011) – it is one of the most famous *intraplate* seismic events. Crone et al. (1997) estimated these earthquakes have a recurrence interval of ~100,000 years in what Johnston (1996) classified as a stable continental region (SCR). Searching for seismicity precursors, Bowman (1997) states "the epicentral area had been virtually aseismic prior to 1986". However, other than noting their explosions as seismic sources, Bowman, like nearly all investigators, ignores the seismogenic potential of the many Tennant Creek mines whose on-going deformation had already been observed by the mining industry (Szwedzicki 1999; 2001).

Tennant Creek was founded in 1932 as a mining town during the last Australian gold rush – Figure 1 shows that the surrounding district within a radius of about 30 km is riddled with mines – it was once the 3rd largest gold producer in Australia (ResourceStocks 2009). One of the town's most productive mines, Nobles Nob (2.1 million tonnes excavated, 1948-1985), began as an underground mine, but after a crown pillar collapse in 1965, it was shut down and re-opened in 1967 as one of Australia's first open pit gold mines. After the mine was closed 1985 (and the pumps probably then shut off), the open pit began to fill with water – a year later, earthquakes started happening about 30 km away, near the site of the 1988 epicentres.

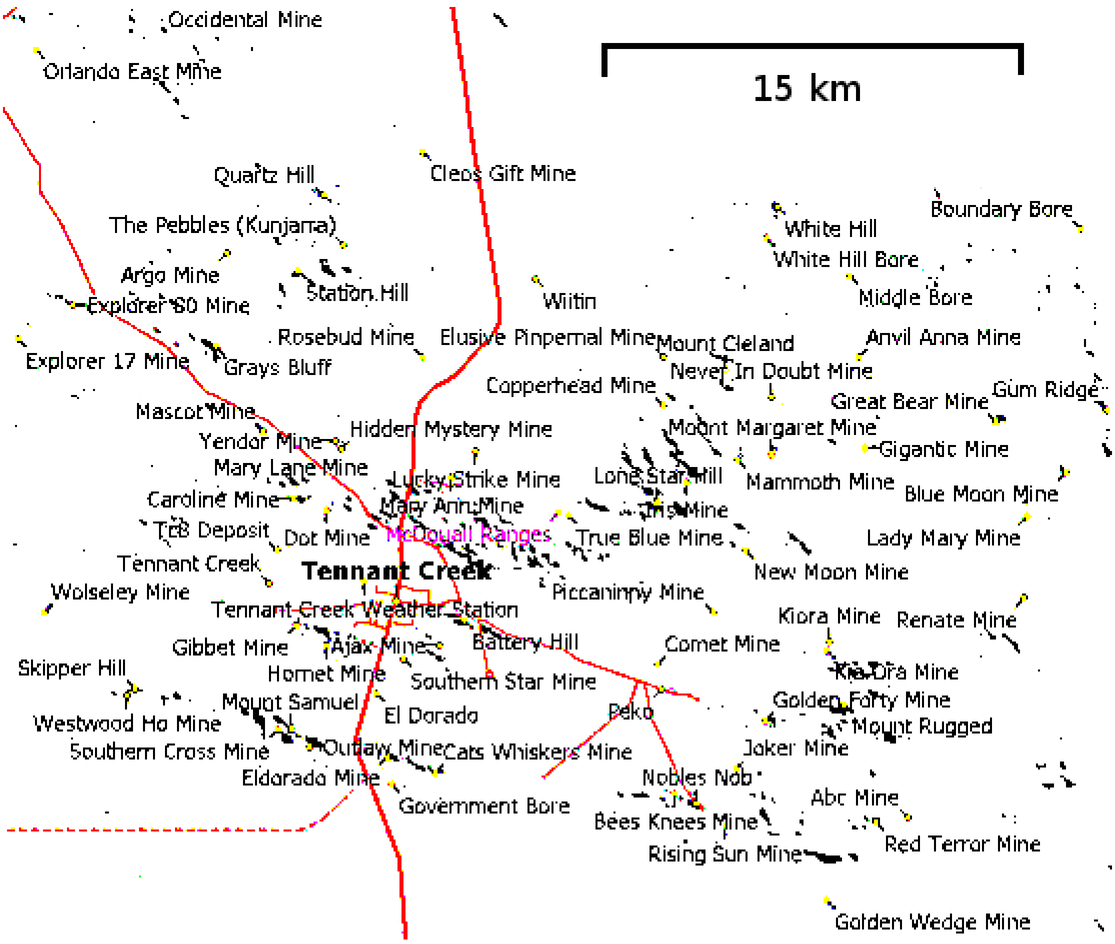

Figure 1 Map showing Tennant Creek mines (modified after <maps.bonzle.com> 2011).

This paper is addressed to the Australian public: it reports on a preliminary survey of the geographic, i.e., spatial, association of mines and earthquakes in Australia, using data and tools available to the public. The data were obtained from the on-line database of Geoscience Australia (2011), and analysed and displayed with MicroSoft Office Excel 2007 (Wikipedia#1 2011). The paper focuses on simple empirical relationships based on everyday intuitions of connection & causality, rather than on more complex models requiring more constrained data and more expertise – when employed, technical terms in *italics* are explained. The global context of Australian seismicity is summarised below.

Australian Seismicity and Plate Tectonics: Earthquakes are an inevitable consequence of continental drift or, more precisely, plate tectonics. The surface of the Earth is broken up into about ten large (1,000-10,000 km wide and 100-400 km thick), more or less rigid, relatively cold and resilient, lithospheric plates that move slowly (1-10 cm/year) around the Earth, supported by the hotter, visco-elastic material of the athenosphere below and driven by its slow-moving convection currents. About 99% of global earthquakes are *interplate* earthquakes that occur – between the plates – at the plate boundaries where the plates *stick/slip* against each other as they jostle each other around the planet.

By contrast, *intraplate* earthquakes occur – within the plates – at some distance from plate boundaries. Although the distinction between *interplate* and *intraplate* can be problematic near boundaries, in the case the of Australian continent, the nearest plate boundaries are several hundred kilometres north of northern Australia or more than a 1,000 km east to New Zealand; hence, all the earthquakes examined here are unambiguously *intraplate*.

Table I. Earthquakes near Mines in Australia: Significant intraplate earthquakes have occurred near operating or historic mine sites in Australia:

Time	**Place**	**Magnitudes**	**Reference**
1988	Tennant Creek, NT	6.3, 6.4, 6.7	McCue (1990)
1989	Newcastle, NSW	5.6	McCue et al. (1990)
1997	Burra, SA	5.1	Mountford et al. (1997)
2006	Beaconsfield, TAS	2.1	Examiner (2006)
2008	Korumburra, VIC	4.6, 4.6, 4.4*	Bathgate et al. (2009)
2010	Kalgoorlie, WA	5.1	Hao (2010)
2010	Cleve, SA	4.8	Love (2011)

*occurred 05 July 2011 after dataset was downloaded, and not included in analysis.

and various events are documented at coal mines in Queensland (e.g., McKavanagh et al. 1995; *NOTE*: references in Table I above are cited as reports on the respective earthquakes, but these reports may not even mention mines). These events are a representative sample of earthquakes spatially associated with mines – the list is not meant to be exhaustive.

Cranswick (2009) discussed three earthquakes in other countries induced or triggered by open pit mining. Cranswick (2010) emphasized the fact that the M5.0 Kalgoorlie earthquake, the largest(?) earthquake at an Australian mine, occurred at Australia's largest, hard-rock, open pit mine – less than a mine's length from the mine itself. McGarr et al. (2002) state, "Perhaps the most straightforward factor influencing the potential for seismic deformation [i.e., earthquakes,] is the size of the region over which an [engineering] activity … takes place", and they present geomechanical analyses to quantify the scale of the stress perturbations produced by mining and the distance range over which these perturbations can induce seismic events in the surrounding rock mass, i.e., country rock.

Ortlepp's 30-km Criterion Separates "Natural" from Mine-Related Seismicity: Ortlepp (2005) reports that in the Kaap-Vaal craton in South Africa, only 8 of the 378 magnitude 3.5–4.0 (M_L) earthquakes recorded in 50 years were "natural" *i.e.*, more than 30 km away from mining activity; hence, 98% were near mines. Ortlepp, a world-renowned rock engineer, chose 30 km as the critical earthquake/mine interaction distance, not for geomechanical reasons, but rather because there were large location errors in the South African earthquake catalogue, and furthermore, a circle with a radius of 30 km encompassed at least five separate mines at the time and, therefore, no single mine owner could be held responsible for damaging earthquakes recognised to be caused by mining (Wolfgang A. Lenhardt, personal communication 2011).

MineQuake Map of Australia: Ortlepp's 30-km criterion was applied to the Australian earthquake and mine catalogues to make a preliminary survey of the geographical association of these two phenomena – see Figure 2. The data consisted of 2,259 earthquakes from the "Australian region" in the magnitude range, $3.5 \leq M \leq 7.3$, during the period, 1800 to 20 May 2011 (Geoscience Australia 2011; accessed on-line {20MAY2011}; Leonard 2008 describes the earthquake catalogue); 1,273 "historic" mines; and, 359 "operating" mines (Geoscience Australia 2011 {18MAY2011}). An Excel Workbook named "MineQuake" was written (i.e., assembled from critical components provided by David Kimble and Virginia R. Ward) to calculate the great circle distance between all earthquake-mine pairs, flag those pairs separated by 30 km or less, and plot the results on a map.

All MineQuake maps in this paper are polar projections on to Cartesian (East, North) axes in units of kilometers. Figure 2 is centred on Alice Springs and covers the widest expanse of all the maps – at the range of 2,500 km (indicated on the axes) which encompasses all of its map features, map distortion is less than 3%.

Circle&Cross Colour Code of MineQuake Maps: Earthquake epicentres are represented by circles scaled in size to earthquake magnitude (later explained). **Green** circles are earthquakes >30 km from all mines, **red** circles are earthquakes <30 km from at least one mine, hence, *minequakes*. The locations of mines, "historic" and "operating", are marked by the symbols, '+' and 'X', respectively. Mines >30 km from all earthquakes are **blue**, mines <30 km from at least one earthquake are **red**. The MineQuake small-scale, detail maps that follow (Figures 3-5) are centred on different named locations and vary in range as indicated on the East, North axes.

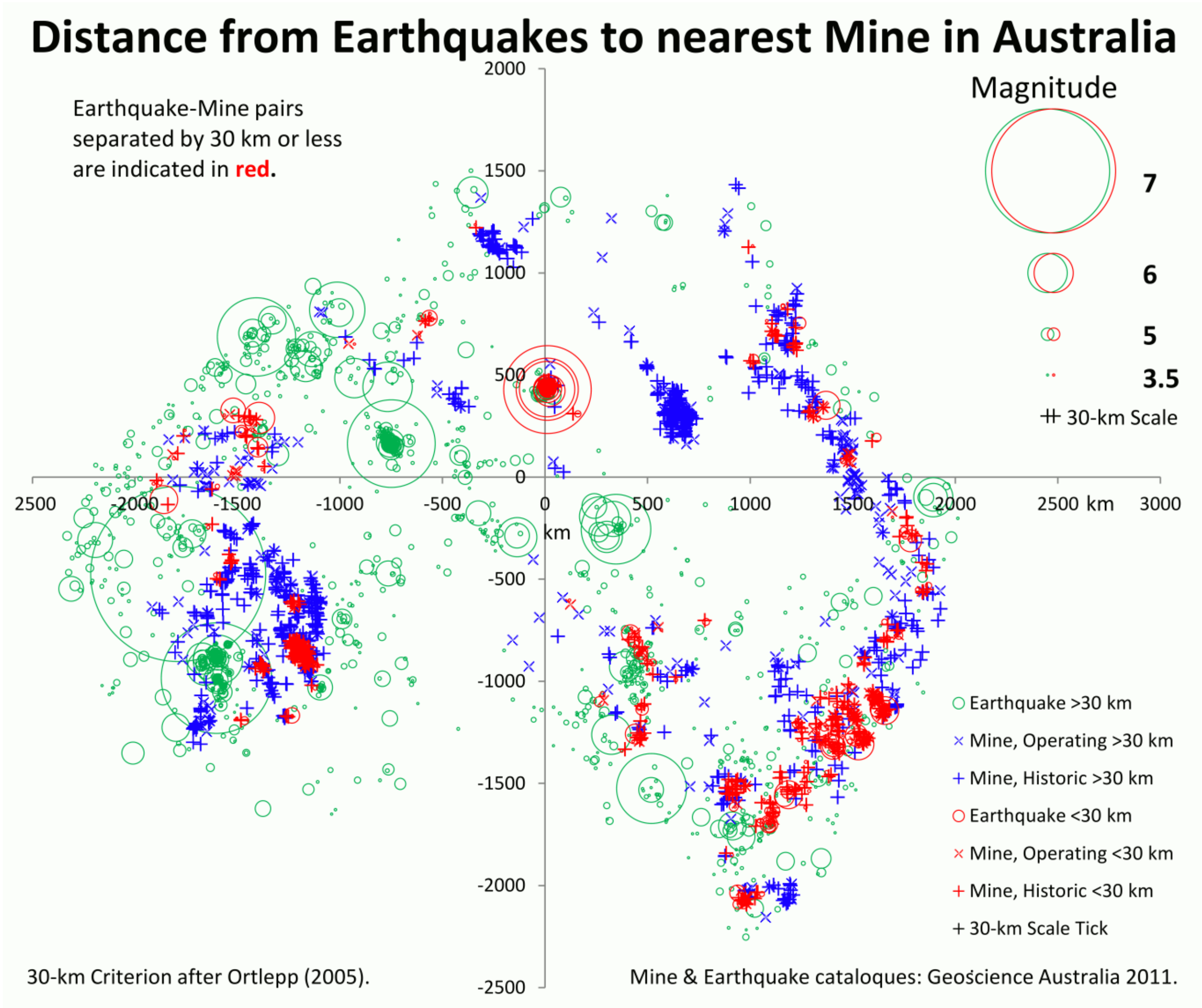

Figure 2. Map illustrating the proximity of earthquakes to mines in Australia – the epicentres of 2259 earthquakes with magnitudes ≥3.5 since 1800 in the "Australian region" (Geoscience Australia 2011) are shown as circles scaled in size to earthquake magnitude (see text). **Green** circles are earthquakes >30 km from all mines, **red** circles are earthquakes <30 km from at least one mine, hence, *minequakes*. The locations of 1273 "historic" and 359 "operating" mines are marked by the symbols, '+' and 'X', respectively (Geoscience Australia 2011). Mines >30 km from all earthquakes are **blue**, mines <30 km from at least one earthquake are **red**. (Figure generated by MineQuake).

Oz Dreaming … Impressions of Seismicity&Mining: 1) The distribution of mines & earthquakes outlines the **Australian continent** fairly well (courtesy of Geoscience Australia for having already filtered the locations of the "Australian Region" earthquake dataset) in a diverse mix of colours – **green & blue: earthquakes & mines apart**; **red&red: earthquakes&mines together** – but there are several large areas (~500 km across) of **white space**, i.e., **no mines or earthquakes**. 2) The **larger earthquakes, >M6** (including the largest, the M7.3 1941 Meeberrie Earthquake, WA; Geoscience Australia 2004) are **green** (except for Tennant Creek), i.e., **far from mines**, and those **near mines**, the **red** earthquakes, are **moderate in size, M4-5** (Virginia R. Ward, personal communication 2011). 3) **Tennant Creek, NT**, is the **red bullseye** of **three larger earthquakes, >M6**, and many smaller earthquakes & many mines. 4) By contrast, the town of **Mount Isa, QLD**, is solid **blue**, i.e., many mines, no earthquakes. 5) The **coast of Western Australia** (WA) is **green**, i.e., many earthquakes, few mines. 6) **Kalgoorlie, WA**, is an intense **red** spot, i.e., many mines & earthquakes, in a band of **blue**; i.e., many mines, no earthquakes. 7) In **northwest WA**, earthquakes & mines are more intermixed and dispersed. 8) **Flinders Ranges & Adelaide Hills, SA**, show one of the most intense and well-defined bands of seismicity (other than the intense aftershock zones of several large **green** earthquakes) that is all **green**&**red** – the only **blue** is a few mines on the periphery, i.e., most of the mines are near earthquakes and **red** – but there are also some single mine outliers, **blue & red** in **northern SA**. And, 9) In the same way that even those of us who do not know country can nonetheless recognise that **Aboriginal art** is telling us something about the country that we would not otherwise notice, the patterns of **East Coast Australia** – **blue**, **red**, **blue**, **green**, **red**, **blue**, **red**, **blue**, **red**, **red**, **red**, **blue**, **green** – share a common internal motif over an extensive range from northern tip of **Cape York, QLD**, to **Tasmania** and including **eastern Victoria**, that distinguishes them from the more diverse distributions of mines & earthquakes in **the rest of Australia** … *there's something going on over there* … of varying intensity but a persistent pattern of **mining&seismicity intertwining together** down along the **eastern coastal plain** … ringing **red,red,red** around **Sydney, NSW**, between the old coal-mining towns of **Newcastle, NSW** to the north, and **Wollongong, NSW** to the south … **well-correlated with population density** (recognising Keilis-Borok and Kossobokov 1990's pattern recognition of seismic phenomena).

MineQuake Limitations: Only the mine locations and classifications ("operating" or "historic") are used by MineQuake – it does not correlate mining activity and seismicity in time, i.e., there is no attempt to determine the relative timing of the two phenomena, only their geographic coincidence. Figure 3A is a MineQuake detail map centred on the epicentre of the M6.7 Tennant Creek earthquake that illustrates the problematic results of applying the 30-km criterion to the complex 1988 Tennant Creek seismic sequence, consisting of three "mainshocks" and many distributed aftershocks. The same data are plotted on the same base map in Figure 3C, but the radii of the earthquake circles are set to 30 km to demonstrate in precise detail the operation of the 30-km criterion.

Figures 3A & 3C show that the centre of the seismic activity that commenced in 1986 according to Bowman (1997) and continues to have aftershocks today is approximately 30 km SW of about 20 mines that surround the town of Tennant Creek (see Figure 1). These mines lie roughly on a NW-SE line along the trend of the McDouall Ranges,

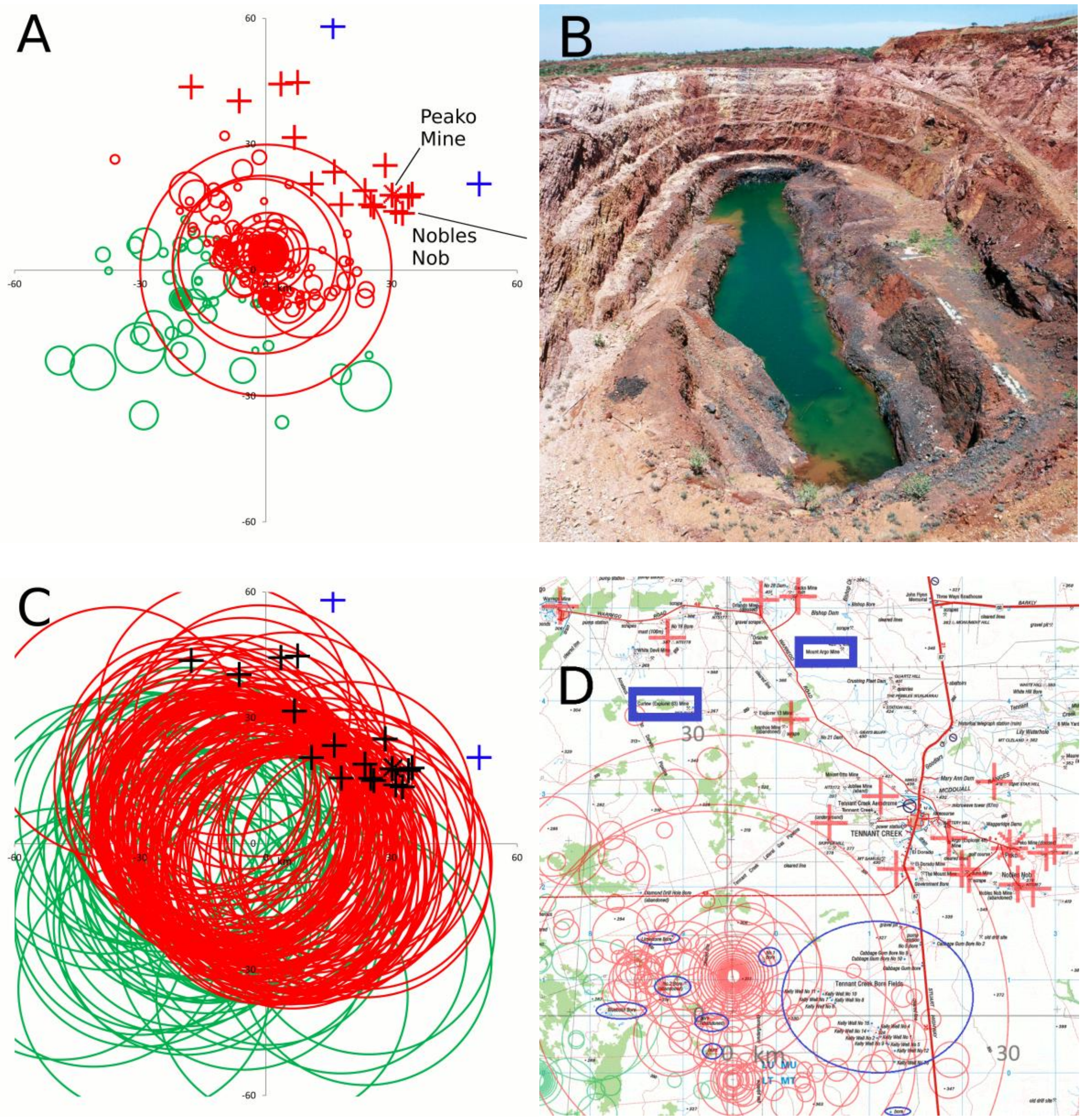

Figure 3. Tennant Creek. **A**) MineQuake map (60 km range) centred on the epicentre of the largest 1988 Tennant Creek earthquake, M6.7, employing the same circle&cross colour code described in Figure 2 except, for the purpose of graphical display and to indicate Ortlepp's 30-km criterion, the sizes of the circles are scaled with magnitude (see text) such that the epicentral event has a radius of 30 km and the smaller events are scaled accordingly. There are eighteen "historic" and one "operating" **red** mines shown, i.e., ≤30 km from one of the many earthquakes shown, and two **blue** mines more than 30 km northeast. The Peako Mine is currently the only operating mine at Tennant Creek, and it is near Nobles Nob, pictured to the *right*. **B**) Nobles Nob open pit mine – flooded (cropped from ResourceStocks 2009). **C**) MineQuake map identical to Figure 3A except all earthquake circles have radii of 30 km to illustrate the workings of the 30-km criterion, and the "red mines" are painted **black** to distinguish them from the dense **red** earthquake circle background. **D**) Section of Figure 3A superimposed on a 1:250,000-scale topographic map (Geoscience Australia 2005) of the mining/epicentral area that shows not only the nineteen **red** catalogued mines marked on the topo map, but also two additional mines marked on the topo map, outlined by the **blue** rectangles, that are not in the catalogue. The **blue** ellipses outline the locations of the "Tennant Creek Bore Fields" and other single bores in the epicentral region.

roughly perpendicular to the SW direction to the epicentral area. Hence, the three 1988 "mainshocks" and most of the aftershocks and corresponding faults that slipped during the earthquakes lie just within the 30-km criterion, but many of the locations of the larger aftershocks extend more than 60 km to the SW (one aftershock lies off the map) and lie outside the 30-km criterion. In this case, small variations of the earthquake & mine locations, e.g., errors, can lead to large variations in the relative numbers of near versus far mine-earthquake pairs, i.e., **red** versus **green** & **blue**.

The 30-km criterion produces unstable results in this case because it samples an insufficiently small area relative to the combined seismic source areas of the three earthquakes with a combined equivalent magnitude of ~7. The relatively small M3.5-4.0 earthquakes reported by Ortlep (2005) would have had small source areas (~100 m), been close to the causative mines (~100 m), and not have produced damage beyond 10 km – hence, many distinct and complete mine-earthquake-damage events would be encompassed by the 30-km criterion. By contrast, the ~100 km diameter of the aftershock zone at Tennant Creek (Figure 3A) implies an earthquake preparation zone of comparable extent. This zone would have encompassed the earthquakes & mines and also the bores shown in Figure 3D that may have participated in mine-earthquake pore pressure interactions as the source volume developed (Ito and Zoback 2000), but the 30-km criterion misses the spatial association of these phenomena – it is biased against large events.

Originally a simple quantitative, i.e., statistical, evaluation of the earthquake&mine dataset as a whole was planned, but because of unexpected complexity of the Tennant Creek earthquakes – the first earthquake(s) examined in detail by this investigation – the statistics have been postponed until the qualitative aspects of the results as a whole are surveyed.

Catalogue Completeness: Clearly, the completeness of the catalogues used in this study varies by orders of magnitude over the data's temporal range of more than a century. However, all the data have been accepted as provided – they have not been "corrected" or otherwise modified based on external information. Figure 3D indicates possible incompleteness of the mine catalogue near Tennant Creek – the MineQuake mine locations of Figure 3A are superimposed on a 1:250,000-scale topographic map (Geoscience Australia 2005) and found to approximately match the mine locations marked on the topo; however, there are an additional two mines marked on the topo that are not included in the catalogue. An email was sent to Geoscience Australia (16AUG2011) requesting information about "Data reliability", but there has been no response yet. No attempt has been made to either cross-confirm the mine catalogue (Geoscience Australia 2011) with the mines marked in Figure 1 and/or trace the source of those mine locations.

Precursors to Tennant Creek Seismicity: Tennant Creek has been discussed at some length here both as an exercise to demonstrate how the Ortlepp (2005) 30-km criterion works in detail and as an introduction to this unusual seismic event. Szwedzicki (1999; 2001) discusses the occurrence of various indicators of mine deformation at Nobles Nob Mine prior to the first local seismicity detected by seismologists in 1986. He summarises the sequence of events observed prior to the surface collapse of August

1967 that developed into a sinkhole into which fell 100,000 tonnes of rock:

> "About a week prior to the ground collapse, the extensometer recorded movement due to a large crack opening above the mined-out area.
>
> During the nightshift preceding the collapse, miners working near the area heard rock noises and reported four rock falls; and
>
> A major rock falls was reported 1 h before the main subsidence."

The "rock noises" heard by the miners would have been generated by small seismic events accompanying the increasing deformation of the surrounding rock mass that subsequently collapsed. In short, an entire cycle of precursors followed by a "mainshock" was not detected by seismologists at the then-operating, fortuitously adjacent, Warramunga seismic array (Bowman 1997), 20-40 km southeast of Nobles Nob Mine, either because the high-frequency signals of these small, shallow seismic events were strongly attenuated over short distances and/or exceeded the recording bandwidth of the array (Cranswick 1988), or the signals may have been discarded as mine-produced "noise" – but that does not mean that the precursors did not exist.

Crone et al. (1997) shares this faith that since some seismic instruments operating somewhere do not appear to be recording anything (assuming one had a sufficient security clearance to be told), therefore, nothing is happening: "Thus, in stable continental settings, microseismicity is an unreliable criterion for detecting all potentially seismogenic faults." The reliable monitoring of precursory seismicity might be feasible in a place like San Francisco where there are about 100 seismographs within 100 km range of the city, but its applicability to inland Australia is limited – the only ones up there monitoring faults in that detail are the miners.

Kalgoorlie Denial: "The magnitude 5.0 earthquake that occurred at 8:17 am on 20 April [2010] near Kalgoorlie Boulder WA caused some building damage, mainly in the Boulder city centre along and around Burt Street. It also caused two minor injuries. This is the fourth earthquake that has caused damage in Western Australia since the Meckering earthquake in 1968." (Hao 2010; see also McCue 2010)

A highly informal poll initially conducted by the author while riding from Perth by pushbike to Kalgoorlie in May 2011 revealed that two respondents on the road (non-residents) believed the earthquake probably had something to do with the Super Pit, but it was unanimously believed (6 out of 6 respondents) by Kalgoorlie residents – *It Is Known!* – that the mine had nothing to do with the earthquake, a matter of faith even to a woman born&raised in what was formerly the east side of the town of Boulder, now disappeared into the Super Pit. However, subsequent discussion with another Kalgoorlie resident and inspection of the house that she had owned and lived in for ~20 years, located above Mt Charlotte Mine, indicated both damage to the house related to mining activity and prompt confirmation of her reports by the mining company, KCGM (2011).

Daniell (2011) cites a "Government" estimate of the total cost of damage as $7.5m (expected range $4.47m-$15m), so the $7.5m question is: "Who pays?" – it depends upon the earthquake. If it were "natural", i.e., an act of God, then insurance companies pay; if it were caused by the mine, then the mine pays (based on conversations with various anonymous individuals in and around the York Hotel, Kalgoorlie, May 2011) – like all things, our seismotectonic understanding has a price … but Ortlepp (2005) says:

> "In Australia, rockbursting was first experienced as a significant but relatively infrequent problem in the Kalgoorlie district in the early part of the last [20th] century. During the last decade of the century [1990's], as the extraction of the deepest massive orebodies of the Mount Charlotte mine peaked, several very large mining-induced tremors were experienced. Six seismic events between M_L 2.5 and M_L 4.3 (Richter scale) were recorded."

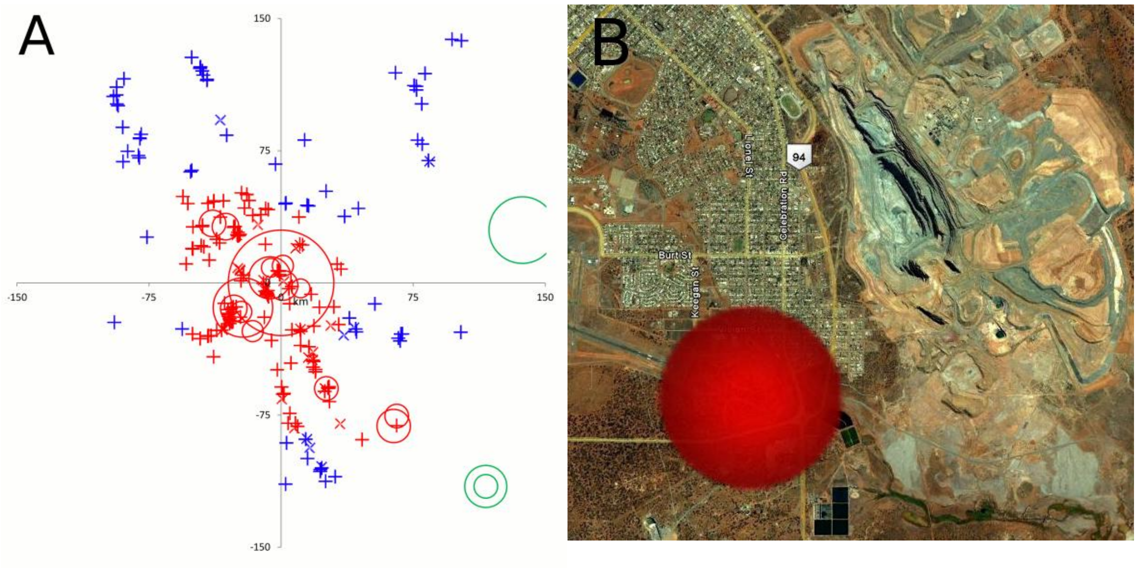

Figure 4. Kalgoorlie/Boulder, WA. **A**) MineQuake map (150 km range) of the epicentre of the M5.0 20APR2011 earthquake, employing the same circle&cross colour code as Figure 3A; *NOTE:* the locus of mines defines two lineaments along the local NNW-SSE tectonic trend which is also reflected in the NNW-SSE long-axis of the Super Pit; **B**) GoogleEarth photograph (Imagery Date 12SEP2004) showing the Super Pit and the M5.0 epicentre in Boulder as the solid red circle 2.4 km in diameter that represents the Brune (1970) *source radius* of the earthquake (see text; modified from Cranswick 2010); *NOTE:* the Super Pit has grown substantially since the photograph and is now ~4 km long.

Based on the 72 mines that responded to their 148-question survey circulated to 135 mines in 18 countries, Hudyma and Potvin (2004) conclude: "The incidence of high seismic hazard appears to be somewhat greater in western Australia compared with underground, mechanized, hardrock mines elsewhere in the world." The fact that mines cause earthquakes is known and well-understood in life/death detail by the rock engineer who makes the decision to blast a stope that may trigger/induce a seismic event that causes a rock burst in the mine that kills the workers or so frightens them that they never want to do that again.

> *If there have been several years of drought, temperatures have been over 40 degrees for a week and a hot north wind is blowing, and someone throws a lit*

cigarette out the car window and there is a bushfire, what caused the fire? Was it natural? Who is responsible?

If there is a stable continental region known to have high horizontal compressive stresses, and a 1/2-km-deep, 4-km-long open pit mine is excavated and there is a shallow, magnitude 5 earthquake within a pit's length of the pit, what caused the earthquake? Was it natural? Who is responsible?

Faults & Earthquakes: The solid red circle shown in Figure 4B that represents the epicentre of the M5.0 Kalgoorlie earthquake has a radius of 1.2 km (diameter = 2.4 km) which is its Brune (1970) *source radius*. The earthquake mechanism is modelled as a spherical *source volume* of rock mass that is elastically deformed, i.e., strained, and divided in half by the fault plane. When the fault slips, the two halves are released to move abruptly some distance in opposite directions, propelled by the restoring stress of the elastic deformation of the volume and resisted by the sliding friction of the fault. Both of these stress components are combined in the quantity, *stress drop*, a measure of the sum of the stresses acting on the rock mass at the instant it begins to slip. The abrupt movement of the two halves generates a *seismic moment* – an impulse, i.e., a push/pull generated by the sudden slip, that propagates in all directions … at the surface, it shakes the ground and structures, etc., and produces a maximum wiggle on a seismograph – that is proportional to the product of the stress drop and the area of the fault that slipped.

Given that other factors are equal, e.g., the elastic & frictional constants throughout the rock mass and the stresses acting upon it, the magnitude, M, of an earthquake is equal to a constant plus the base_{10} logarithm of the area of the fault that slipped during the earthquake. Therefore, the fault area of an M6 earthquake is 10 times the area of an M5 is 10 times that of an M4, etc., and the radii scale accordingly by factors of the square root of 10, i.e., ~3. The areas of the earthquake circles of the circle&cross colour code are proportional to the areas of the faults and preserve their respective size relationships.

The letter, "M", is used here to refer to the value of earthquake magnitude provided, however it may or may not be defined, e.g., M_L, M_S, m_b – it is implicitly assumed to be M_W. The Hanks & Kanamori (1978) moment-magnitude scale (M_w) was used to estimate the seismic moments of earthquakes from their given magnitudes, M, and the seismic moments used in turn, for a given stress drop, to calculate the respective Brune source radii of the epicentre circles of the circle&cross colour code. A standard value of stress drop, 10 MPa, and standard values of other physical parameters were used to calculate the source radius of Figure 4B. In all the other MineQuake maps, unphysically small values of stress drop are used for graphical convenience – to make the circles large enough to be visible.

East Coast Australia: The M5.6 1989 Newcastle earthquake (McCue et al. 1990), one of the largest earthquakes in the sprawl of **red** patches around Sydney shown in Figure 5, was Australia's most lethal, 13 dead, and expensive, $4-billion, earthquake. The **red** mines&earthquakes that trace the outcrop of the Illawara Coal Measures in this region are a contentious issue: Klose (2007) argued that the Newcastle earthquake was triggered/induced by the long history of coal mining in the region; the Government of New South Wales (Quinna et al. 2008) responded that it was not (*NOTE:* the NSW Government receives ~$1-billion/year from coal mining royalties; NSW Dept. Primary

Industries 2011).

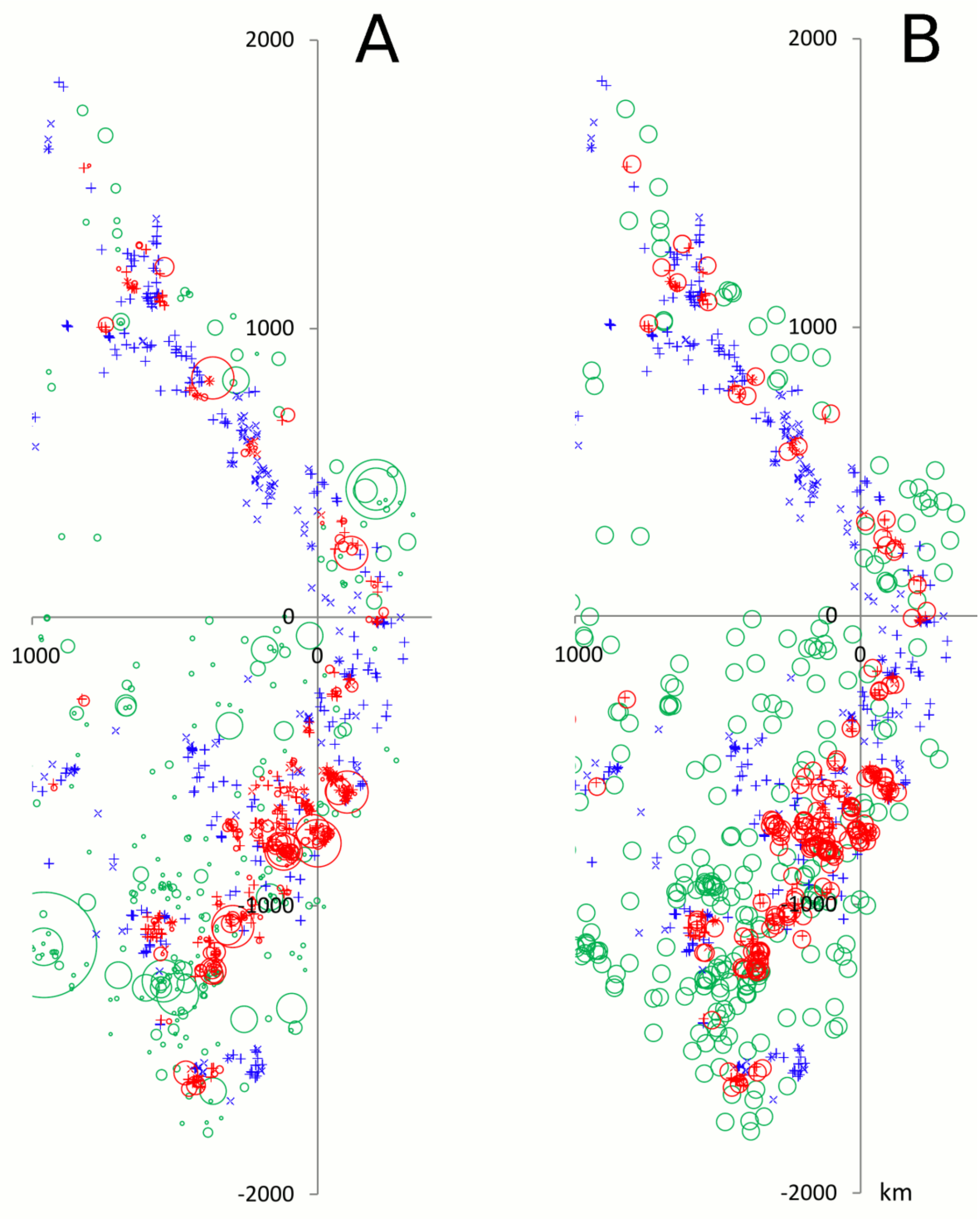

Figure 5. MineQuake maps (range: 1,000 km E; 2000 km N) of East Coast Australia, centred ~200 km inland from Brisbane, QLD, and employing the circle&cross colour code with earthquake circles: **A)** scaled with magnitude; **B)** set to 30 km radii to show 30-km criterion.

The abstract cited in full below, "Discriminating between Blasts, Collapses and Natural Seismic Events" (Cuthbertson and Payne 2011) provides some insight into the seismological complexities related to this controversy.

> "The primary aim in the operation of most seismograph networks is to identify natural earthquake activity. This activity is frequently obscured by "man-made" seismic events – most typically blasts from extractive industries but also from underground collapses of coal mines. Distinguishing between natural and man-made events is usually made by the analyst primarily on the basis of waveform: the presence or absence of surface waves; coda shape; and the impulsiveness of phase arrivals. Other criteria used for ambiguous events are location (proximity to existing extractive industries) and time of day (blasting being restricted to daylight hours) but these criteria can be misleading: a natural event may occur near a mine; a collapse can occur outside normal blasting hours. The use of dilatational first motions to signify an earthquake (as opposed to a blast with first motions always compressional) can also be misleading as collapses will also have dilatational first motions. Distinguishing between the various sources requires knowledge of the history of the seismic and mining activity in an area, as well as carefully documented examples of positively identified events to use for comparison. Examples from the operation of a seismic network in central New South Wales, Australia will be used to demonstrate this procedure."

The abstract as a whole raises some questions about the reliability of the MineQuake catalogue (Geoscience Australia 2011), but the first sentence of the abstract asserts a problematic assumption, "The primary aim … is to identify natural earthquake activity." This ignores the history that seismology was revolutionized in the 1950's-1960's, leading to the elucidation of the role of earthquakes in plate tectonics, and paid for by the US Air Force in its mission to monitor underground nuclear explosions in the USSR.

The nominal mission of the seismologists then was to develop seismological techniques to verify compliance of a comprehensive (nuclear) test ban treaty (CTBT) as the first step towards halting the testing of nuclear weapons, and then, eliminating them altogether (Evernden et al. 1986). The US Government did not actually want to stop testing, let alone, give away its nuclear weapons – as a cover, US seismologists were essentially paid to demonstrate that seismology did not work, that verification was impossible, to obfuscate the issue. Hence, seismology in the USA became another hi-tech spin-off controlled by the US military/industrial complex, the dominant power in US society – a role played by the mining/financial complex in Australia (Pearse 2009). Similarly, the connection between earthquakes and mines has been obscured by the Australian mining/financial complex.

One of the principal advantages of Ortlep's 30-km criterion is that it eliminates the hi-tech, fine-hair-splitting of the Gordian Knot of source discrimination described above, biased by its attendant legal & financial implications – the criterion was originally designed to do exactly that, for similar South African geopolitical reasons.

Potential Biases in Earthquake Catalogues: 1) Earthquakes near mines are sometimes accidentally misidentified as explosions or intentionally omitted because of public relations. 2) Many of the inland European settlements in Australia, for which consequently there are historic records of seismicity, were established at mine sites. 3) Traditionally, mining starts where ore is exposed at outcrops, which themselves may be manifestations of repeated faulting events – hence, mining may preferentially occur at locations of pre-existing high seismic activity.

Minequakes: The **red** patches on the MineQuake maps represent concentrations of spatially coincident earthquake-mine pairs that are greater than what would be expected from the correlation of two independent, i.e., un-correlated, populations. This suggests that these earthquakes are *minequakes* – that there is some necessary reciprocal connection between the two phenomena – either that the mines cause earthquakes in the sense that the earthquakes would have had a low probability of occurring had the mines not been dug; or that, on a geologic time scale, the earthquakes had caused the mines by raising the topography that exposed ore as outcrop; or, both.

Do mines cause earthquakes or do earthquakes cause mines? As a consequence of the dynamics of plate tectonics, the continent of Australia, like most continents, is largely in a state of horizontal compression that tends to buckle it and uplift mountains. This tendency is counteracted by vertical compression, i.e., the weight of mountains, which acts to keep the land low&flat, by erosion which reduces the topographic relief back to sea-level, and by the inherent strength of the rock mass to resist both deformation and erosion. Where the continent is weak, it fails under horizontal compression in a series of earthquakes that have the effect of shortening the continent and thickening it, i.e., making it stronger at the point of failure, until it resists further failure there; hence, raising mountains that resist the further rise of mountains. As erosion slowly continues to remove some of the top of the continent, to make it thinner, the continent fails again, and again.

Because of its lack of topographic relief and its great distance from plate boundaries, and because it did not experience continental glaciations during the Pleistocene (i.e., glacial rebound is a major cause of earthquakes in the Fenno-Scandian Peninsula) – the Australian continent is characterised by very slow deformation, i.e., by low strain rates. The Australian continent has been in this suspended state of tectonic/erosional equilibrium for millions of years – Twidale and Campbell (1988) believe that ancient relict continental surfaces are preserved in the Northern Territory & Western Australia.

Both Tennant Creek and Kalgoorlie are hardrock mines sited in very old geologic provinces that have: 1) considerable topographic relief above the average altitude of Central Australia; 2) high ratios of horizontal/vertical compressive stress, measured *in situ* (see below). This suggests that the thrust faulting of compressional tectonics has acted, in concert with *denudation* (erosion of the younger rocks), to bring old and deep ore deposits to the surface where they outcrop and can be detected by traditional prospecting methods and exploited relatively easily. It implies that this was and possibly continues to be, as manifested by its relief, a seismically active area – **earthquakes cause mines**.

Assume there are high ratios of horizontal/vertical compressive stresses within the rock mass that are in equilibrium with the strength of the rock mass. The introduction of a mined cavity into the rock mass perturbs the state of stress in the surrounding rock mass to a distance of a few times the length of the cavity. As a consequence of being in equilibrium, some portions of the rock mass are already critically close to failure (and may have been for ~100,000 years), and perturbations can lead to failures – **mines cause earthquakes**.

Blue Spot, Mt. Isa – Many Mines, No Earthquakes: The extraordinary concentration of mines and absence of earthquakes at Mt. Isa is unique in Figure 2. Two related factors may explain this: 1) the rocks mined there, dolomite & shale, are sedimentary and soft; 2) the ratios of horizontal/vertical compressive stresses there are about one third (1/3) less than those of the two hardrock mines (see Table II below).

Table II. Mean Horizontal/Vertical Ratios of *In Situ* Stresses at Three Mines

Mine Location	**Horiz /Vert**	**No. Obs.**	**Rock Type**
Mount Isa Mine, Qld.	0.96	4	sedimentary
Warrego mine, Tennant Creek, NT	1.59	3	hardrock
Mount Charlotte mine, WA	1.43	3	hardrock

Data from Brown and Hoek (1978)

Outside/Inside the Mine: How many earthquakes can occur near a mine that have nothing to do with the mining activity? How many earthquakes with 100,000-year intervals can occur in the Australian continent within a 50-year interval? Cuthbertson (2011) describes a method of filtering seismicity data, "This approach had been applied to eastern Australia to provide a quantitative, unbiased comparison of seismicity parameters across the region" – mining is not mentioned. What do seismicity parameters mean if the earthquake statistics are dominated by earthquakes caused by mining? It is frequently argued that mines do not cause earthquakes because earthquakes have been occurring long before there were mines. Death also occurs naturally, but it can also be brought about prematurely by murder.

This study did not intend to prove or disprove that some particular earthquake was caused by mining – Tennant Creek and Kalgoorlie were initially examined in detail to demonstrate the operation of the 30-km criterion – but the results here indicate many minequakes that merit further investigation. In recent controversies regarding the perturbation of various Gaian feedback loops, i.e., Earth systems, such as global climate, groundwater, and intraplate seismicity, the burden of proof has been on the perturbed rather than the perturber – this bias should be reversed.

From a phenomenological perspective of the continent as a whole (Figure 2), it appears that mining causes a significant fraction of Australian seismicity – recognizing this is a necessary step to separating "natural" seismic events from all the others.

In the first part of his paper, "Modelling Seismic Hazard for Mines", Mendecki (2011) establishes the primary cause of seismicity in mines: "*Ceteris paribus* [all things being equal], seismic hazard in mines [induced seismicity] is driven by volume and the spatial and temporal distribution of rock extraction." A crucial question implicitly posed but not answered by the paper concerns the interaction of the mine environment in which the "seismic rock mass response to mining can be controlled" with the encompassing plate tectonic environment in which "Earthquake driving forces cannot be controlled" – where is the boundary between the mine and the rest of the Earth, and how are conflicting the boundary conditions between them resolved?

As an example of this ambivalence, consider the seismic hazard assessment of the planned open pit mine at Olympic Dam – what is the magnitude of the largest earthquake expected at the mine? Based on the open pit's dimensions, 4.1 x 3.5 x 1 km deep, a geomechanical model (McGarr et al 2002) gives an "inside the mine" estimate of magnitude 4-6, i.e., an induced earthquake like Kalgoorlie. Based on the 35-km length of the Mashers Fault that passes through the middle of the ore body to be mined and beyond the mine boundaries, a geological model (Wells and Coppersmith 1994) gives an "outside the mine" estimate of magnitude ~7, i.e., a triggered earthquake like Tennant Creek. (Because source similarity is not constant in the source scaling model of Medecki 2011, it could not give the magnitude of the earthquake expected from the excavation of ~5 km^3).

Conclusions: Sandiford (2010) argued that the energy and mass transfer rates of anthropogenic processes are now comparable in magnitude to those of plate tectonic processes – the "Mine" expands to encompass the whole Earth. This implies – following the relation of Mendecki (2011) between the volume of rock mass mined and the induced seismicity – that as the mining industry expands, intraplate seismicity will be increasingly dominated by earthquakes caused by mining.

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