Mashers Fault and the Seismicity Anticipated to be Stimulated by the Proposed Open Pit Mine at Olympic Dam

Edward Cranswick

Public Seismic Network (Geophysicist, US Geological Survey, retired)
12 Bowillia Ave, Hawthorn, SA 5062, Australia.
Email: e_cranswick@yahoo.com

Abstract The proposed excavation at Olympic Dam of one of the largest open pit mines on Earth, 4.1 km long, 3.5 km wide, 1 km deep, at a bend in the steeply dipping, 35-km-long Mashers Fault, and the associated perturbation of the local groundwater pore pressures in a region of horizontal compressive stress would most likely stimulate local seismicity. Faulting, perhaps related to variations of pore pressure, has occurred intermittently on structures in Australia that are difficult to recognise, and open pit mines have caused earthquakes in other countries. Removing 1 km of rock at Olympic Dam would reduce the vertical stress by ~25 MPa, increase the deviatoric stress and facilitate thrust-type faulting in the vicinity of the open pit, and possibly stimulate strike-slip failure on the Mashers Fault, triggered by the extensive pumping and disposal of ground water. Relatively small (magnitude <6), local earthquakes might damage the Tailings Storage Facilities and release their radioactive tailings to contaminate ground and surface waters and be transported throughout Australia by dust storms.

Keywords: seismicity, Olympic Dam, Mashers Fault, induced, triggered, earthquake

Introduction Broken Hill Proprietary (BHP Billiton) currently owns and operates the existing underground copper-uranium-gold-silver Olympic Dam mine (coordinates: –30.44°, +136.87°) 10 km km north of Roxby Downs in South Australia (Figure 1). The company has proposed in their *Olympic Dam Expansion Draft Environmental Impact Statement 2009* (ODXdEIS; BHP Billiton 2009) to expand the mining operation over a period of 40 years and create an open pit mine 4.1 km long, 3.5 km wide, 1 km deep – making it one of the largest open pit mines on Earth.

The Olympic Dam ore body is a hematite breccia within the basement of Palaeoproterozoic and Mesoproterozoic crystalline rocks that are unconformably overlain by ~300 m of Neoproterozoic to Cambrian age, flat-lying sedimentary rocks of the Stuart Shelf and a veneer of surficial deposits on the eastern margin of the Gawler Craton (Reynolds 2001; see Figures 2 & 3). The mined ore is ground into particles and treated with acid to dissolve and remove copper, uranium, gold and silver, and the resulting tailings are a slurry that is pumped to the Tailings Storage Facility (TSF). There the tailings solids are allowed to settle and the liquid component is removed by evaporation and seepage into the surficial layer of sands and clays (~3 m thick) and the underlying shallow aquifer of the Andamooka Limestone, and some excess liquid drains into evaporation ponds (ODXdEIS).

Currently ~8 Mtpa (million tonnes per annum) of tailings solids and 8.5-9.0 GLpa (gigalitres per annum) of liquid are discharged into the TSF. With the expansion of the mine, the production of tailings solids would increase by an additional 58 Mtpa, and this would necessitate the construction of 9 additional TSFs. These would be square dams 2,000 m on a side constructed of 65-m-high rock walls that enclose 400 hectares of un- and semi-consolidated material – one of the most critical design criteria at Olympic Dam is to ensure the stability of these TSF structures (ODXdEIS).

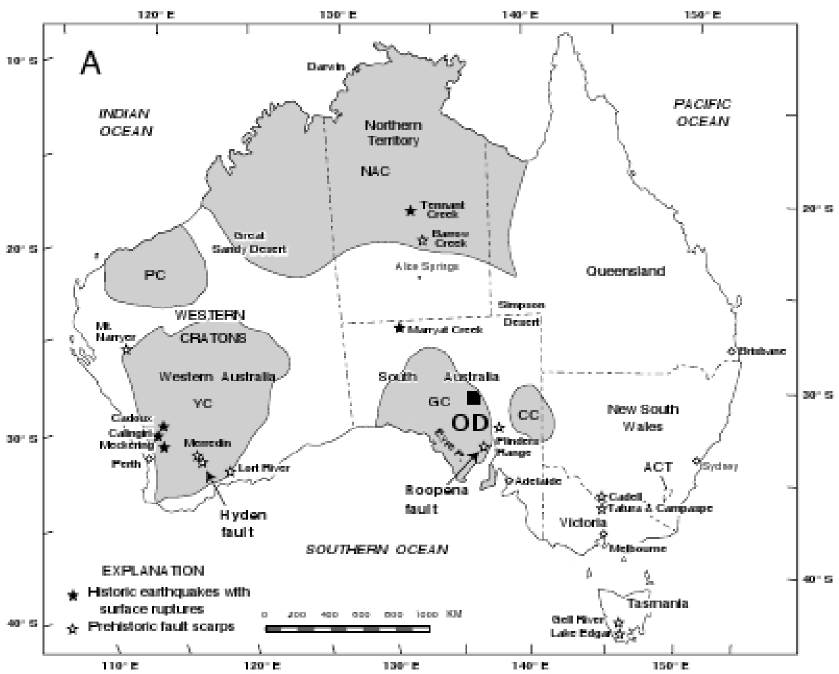

Figure 1 Map of Australia showing the location of Olympic Dam (black square above "**OD**") with respect 'to historical surface-faulting earthquakes (solid stars), reported prehistoric fault scarps (open stars), and general extent of selected cratons … YC, PC, GC, CC, and NAC are the Yilgarn, Pilbara, Gawler, Curnamona, and North Australia cratons, respectively' (adapted from 'Figure 1.A', Crone et al. 2003).

Next to the ore body, the most prominent geological structure at Olympic Dam is the 35-km-long Mashers Fault that passes through the middle of the ore body and the proposed pit (Figures 2, 3, 4). The excavation of the open pit mine and the associated perturbation of the local groundwater pore pressures would most likely stimulate some level of seismicity in the vicinity of the mine, and possibly slip on the Masher Fault itself. I use the term "stimulate" as defined by McGarr et al. (2002):

> '"induced" describes seismicity resulting from an activity that is comparable in magnitude to the ambient shear stress acting on a fault to cause slip, whereas "triggered" is used if the stress change is only a small fraction of the ambient level … By "stimulated" we refer generally to seismicity either triggered or induced by human activities.'

This paper developed from a general critique of the ODXdEIS with respect to the seismotectonic implications of and possible consequences to the proposed open pit mine (Cranswick 2009) and from an earlier note about seismic hazard&risk in the district (Cranswick 2003), but this paper focuses on the significance of the Mashers Fault.

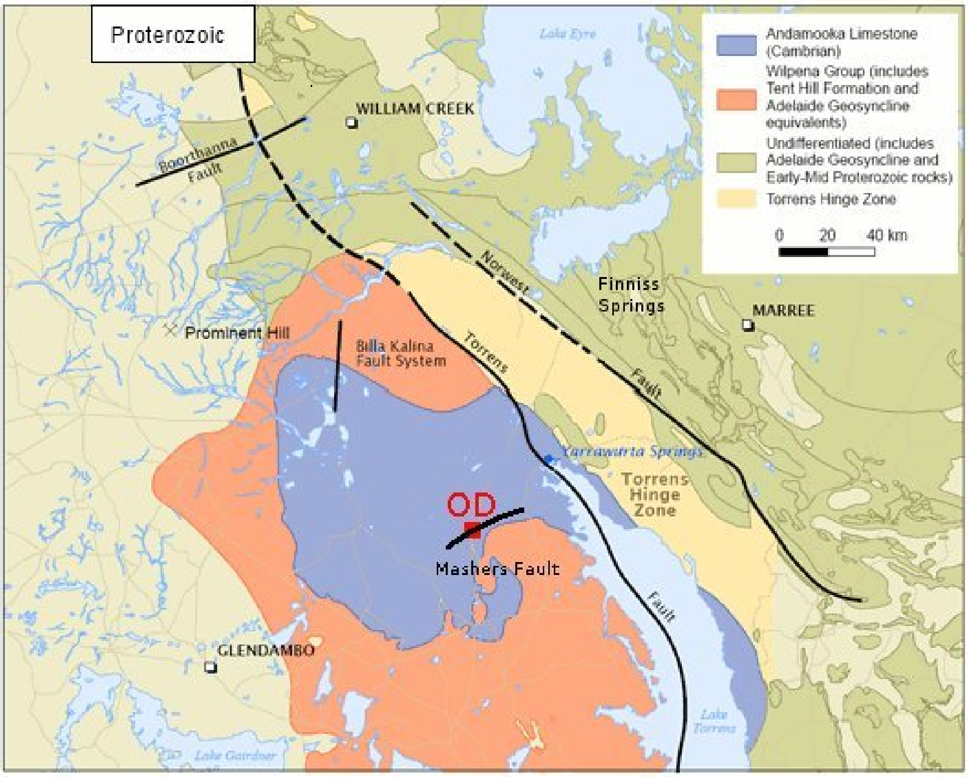

Figure 2 Map of key Proterozoic geological formations of the Stuart Shelf which shows the Mashers Fault, passing through the middle of Olympic Dam (red square below "**OD**"), and the Torrens Hinge Zone, bounded by the Torrens and Northwest Faults (modified from 'Figure 2-2', *Appendix K Groundwater and Geochemistry*, ODXdEIS)

ODXdEIS Seismic Hazard&Risk The section on seismic hazard&risk in the *Main Report* of the ODXdEIS is less than a page. It states 'Earthquakes that measure 5.5 to 6.1 may cause slight building damage' – this may surprise the citizens of Newcastle, NSW, 13 of whom were killed by the magnitude 5.6 1989 Newcastle earthquake (McCue et al. 1990) that caused AUD$4 billion damage (Wikipedia 2009). It discusses the earthquake catalogue of South Australia and emphasises recent, small earthquakes but does not mention the damaging magnitude 5.4 1954 Adelaide earthquake that resulted in more than 30,000 insurance damage claims (Sinadinovski et al. 2006). Citing the "Earthquake Hazard Map of Australia 1991" (McCue et al. 1993), it estimates that ground accelerations at Olympic Dam have a 10% chance of exceeding 0.09 g (acceleration due to gravity) in 50 years.

A more detailed seismic hazard&risk analysis (Environmental Systems & Services, Seismology Centre 2003) done specifically for the TSFs at Olympic Dam is presented in *Appendix F1 Tailings Storage Facility Design Report* (ODXdEIS). Some of the assumptions underlying their assessment are:

> 'The earthquakes considered ... are predominantly much larger distant events, with longer duration of strong ground motion – the type of earthquake that can cause damage to massive structures such as TSFs. … [In] the case of Olympic Dam, the contribution to hazard from earthquakes closer than about 70 km is minimal, with most of the hazard being from larger distant events in the Flinders Ranges [i.e., east of the Northwest Fault in Figure 2] … [that] would allow seismic waves ... to be considerably attenuated before reaching the site'.

Apparently using the 'Equation' of Atkinson and Boore (1995; but which is not included in the References), they estimate a peak ground acceleration of 0.075 g with a return period of 1,000 years.

The critical shortcomings to these analyses are the assumptions that there will be no significant earthquakes near Olympic Dam and that small earthquakes are not damaging. Relatively small earthquakes near or below the site could produce damage not only by strong ground shaking but also by fracturing the ground surface, and such events could be stimulated by the mining operations.

Seismicity Triggered by Open Pit Mining As summarised in Table 1, open pit mines have triggered significant earthquakes on at least three occasions: the magnitude 3.3 1974 earthquake at Wappingers Falls, New York, USA (Pomeroy et al. 1976); the magnitude 4.6 earthquake on 29 November 1980 at Belchatow, Poland (Gibowizc 1982; Gibowicz 1990; Gibowizc et al. 1981); and, the magnitude 4.6 earthquake at 1994 Cacoosing Valley, Pennsylvania, USA (Seeber et al. 1998). All three accounts refer to the principal tectonic stress being horizontal and to unloading the vertical stress by quarrying, and two consider the effect of changing pore pressure as part of the mining operation. All describe prior earthquakes and/or foreshocks and active aftershock sequences.

Australian *in situ* Stress and Tectonics Although the continent of Australia is wholly intraplate and therefore less seismically active than regions near plate boundaries, it has one of the highest rates of intraplate seismicity (McCue et al. 2008). There have been 11 historical earthquakes that have ruptured the ground surface in stable continental regions (SCR) world-wide, and 5 of these events have occurred in Australia since 1968 (Crone et al. 1997). Like most SCR, the Australian crust is characterised by a horizontal compressive stress, and the horizontal stress trajectories in much of Australia, including Olympic Dam, trend approximately east-west (Hillis and Reynolds 2003).

Denham et al. (1980) surveyed *in situ* stresses at or near the surface along a 200-km-long, north-south traverse that included the epicentres of magnitude 6.9 1968 Meckering earthquake (Everingham et al. 1969) and the magnitude 5.9 1970 Calingiri earthquake in Western Australia (Figure 1). They measured the highest horizontal stress of 23 MPa furthest north from the Meckering epicentre and the lowest stress of 4 MPa near the epicentre, from which they inferred that slip during the Meckering earthquake had relieved the regional tectonic stress, and they hypothesise that pore-pressure variations may trigger these events. Horizontal compression with a more NE-SW trend is consistent with the slip of surface-rupturing, thrust earthquakes that have occurred north of Olympic Dam: the magnitude 5.8 1986 Marryat Creek earthquake (McCue et al. 1987) and the three magnitude 6.3-6.7 1988 Tennant Creek earthquakes (Bowman 1992). Those epicentral areas had been essentially aseismic previously: 'as at Marryat Creek, the historical and instrumental record of earthquakes offered no hint of potentially seismogenic faults in the Tennant Creek area' (Crone et al. 1997).

Table 1 Comparison of three earthquakes triggered by open pit mining

	Wappingers Falls, New York, USA	**Belchatow, Central Poland**	**Cacoosing Valley, Pennsylvania, USA**
Date	07 June 1974	29 November 1980	16 January 1994
Location	+41.62°, –073.94°	~ +51.3°, ~ –019.5°	+40.37°, –076.07°
Depth (km)	~1[1]	~3[1?]	2.0±1.0[2]
Magnitude	3.3 (m_b, Nuttli)	4.6 M_L	4.6 m_b(Lg)
Max. Intensity	MMI V	MSK 6-7 ≈ MMI	MMI VI-VII
Damage	2 broken windows	'spectacular'(?)	~US$2 million
Felt Distance (km)	10	100	~50
Mechanism	thrust	reverse, oblique	reverse, left-lateral
Mine Type	limestone	brown coal	carbonates
Open Pit Size (km)	1 x 1 x 0.025	1 x 2 x 0.1	0.5 x 0.5 x 0.015
Overburden (m)	none	100	none
Faults	none aligned	graben[3]	no, but many joints
Pore Pressure	not discussed	water withdrawal	flooded
Stress change (MPa)	0.7[4]	2.5[4]	0.13[5]

Notes 1. Depths estimated from aftershock/foreshocks.
2. Depth determined from broadband waveform modelling.
3. Kleszczow Graben has been intermittently active throughout the Cenozoic (van Loon 2002).
4. Triggering stress decrease caused by unloading.
5. Triggering Coulomb stress increase.

Crone et al. (2003) investigated the Roopena fault scarp near Whyalla, South Australia, roughly 300 km south of Olympic Dam, and the Hyden fault in Western Australia, and they write:

> '[C]ratonic faults in stable continental regions (SCR) typically have a long-term behavior characterized by episodes of activity separated by quiescent intervals of at least 10,000 and commonly 100,000 years or more. Studies ... document multiple Quaternary surface-faulting events that are unevenly spaced in time. The episodic clustering of events on cratonic SCR faults may be related to temporal fluctuations of fault-zone fluid pore pressures in a volume of strained crust. The long-term slip rate on cratonic SCR faults is extremely low, so the geomorphic expression of many cratonic SCR faults is subtle, and scarps may be difficult to detect because they are poorly preserved. Both the Roopena and Hyden faults are in areas of limited or no significant seismicity; these and other faults that we have studied indicate that many potentially hazardous SCR faults cannot be recognized solely on the basis of instrumental data or historical earthquakes. Although cratonic SCR faults may appear to be nonhazardous because they have been historically aseismic, those that are favorably oriented for movement in the current stress field can and have produced unexpected damaging earthquakes.'

According to local Aboriginal tradition, the country between Olympic Dam and Finniss Springs ~100 km to the northeast across the Torrens Hinge Zone (Figure 2) is known for earthquakes (R. Dodd and K. Buzzacott, personal communications, 2006-2009).

Potential for Stimulated Seismicity McGarr et al. (2002) review the mechanisms that maintain the stability of crust and, conversely, promote instability:

> '*In situ* stress measurements made in a variety of tectonic settings, both active and inactive [i.e., SCR], indicate, almost invariably, that the ambient state of stress in the continental crust is quite close to the depth-dependent strength of the crust estimated from laboratory experiments … Moreover, these same investigations reveal that the ambient pore pressure is nearly always close to hydrostatic. Laboratory estimates of crustal strength … are based on stick-slip friction experiments as extrapolated to conditions anticipated at depth in the crust. That is, if the upper seismogenic crust is pervasively faulted then frictional sliding across these faults … will limit the strength of the crust.
>
> The strength of a fault, or the shear stress τ required for failure, can be expressed as
>
> $$\tau = \tau_0 + \mu(\sigma_n - p) \qquad (1)$$
>
> where τ_0 is the cohesion, μ is the coefficient of friction, σ_n is the normal stress across the fault and p is the pore pressure within the fault zone. Laboratory measurements of μ are generally in the range 0.6–1.0 … Thus, for a given state of stress, the strength of a fault would depend upon its orientation, pore pressure, and cohesive strength. In estimating crustal strength it is often assumed that (1) faults exist in the crust that are

optimally oriented for failure, (2) the water table is at the surface (hydrostatic pore pressure), and (3) the cohesive strength can be neglected.
…
Triggered or induced seismicity occurs when the mechanical state of the seismogenic crust is sufficiently perturbed to cause a fault to fail. As indicated by Eqn. (1), failure can occur either because the stress τ loading the fault increases or the strength of the fault is reduced due to a decrease in normal stress σ_n or an increase in the pore pressure *p*.
…
For a number of the case[s] …, the stress changes required to trigger seismicity, as well as the corresponding stress seismic drops (of the order of 1 MPa), are small fractions of the shear stress acting to cause fault slip … indeed, numerous studies … lead to the conclusion that stress changes as small as 0.1 MPa {Eqn. (1)} may trigger earthquakes. This general observation is consistent with the idea that the crustal state of deviatoric stress tends to be nearly as high as the crustal strength … The exception to this generalization is mining induced seismicity for which the stress changes causing the earthquakes are of the same order as the ambient crustal stresses loading the mine workings …'

Mashers Fault The NE-SW-trending Mashers Fault (Figures 3 & 4) is mapped as having a total length of 35 km ('Figure 2-4', *Appendix K Groundwater and Geochemistry*, ODXdEIS), but there are no references to it in the scientific literature. In Figure 3, it is labelled as the 'Mashers Fault Zone', dips steeply to the north (apparent dip ~70°), has a width in the range 100-500 m, and is shown to penetrate the Andamooka Limestone (Cambrian) but not the overlying 'Surficial deposits (sand and clay)'. On the photomap, 'Figure 12.9 Existing wellfields on the Special Mining Lease' (ODXdEIS), it is marked as a conspicuously wide feature that is ~4 km long and trends east-northeast ~1 km south of the Whenan Shaft of the underground mine, and the bores there have significantly high flow rates. It is further described in *Appendix K Groundwater and Geochemistry* (ODXdEIS):

'Complex geological structure within the Tent Hill Formation and basement is interpreted from the large number of lineaments that have been mapped on the Stuart Shelf (Figure 2-4). A major east-west trending shear zone that is coincident with the OD ore body, known as Mashers Fault (Figure 2-4 and 2-7), is observed in all lithological units below the Andamooka Limestone. This fault, and others, has been active since the mineralisation of the OD ore body occurred. In general they strike northwest-northeast, are discontinuous and sometimes have dislocated the cover sequence.'

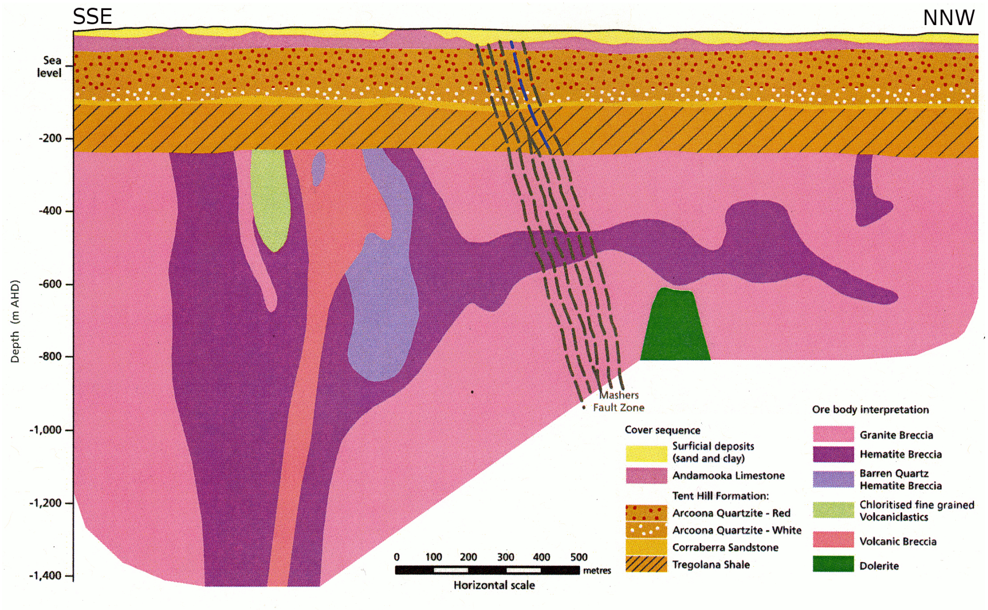

Figure 3 Schematic SSE-NNW cross-section through the Olympic Dam ore body, no vertical exaggeration. (modified from 'Figure 2.5', ODXdEIS).

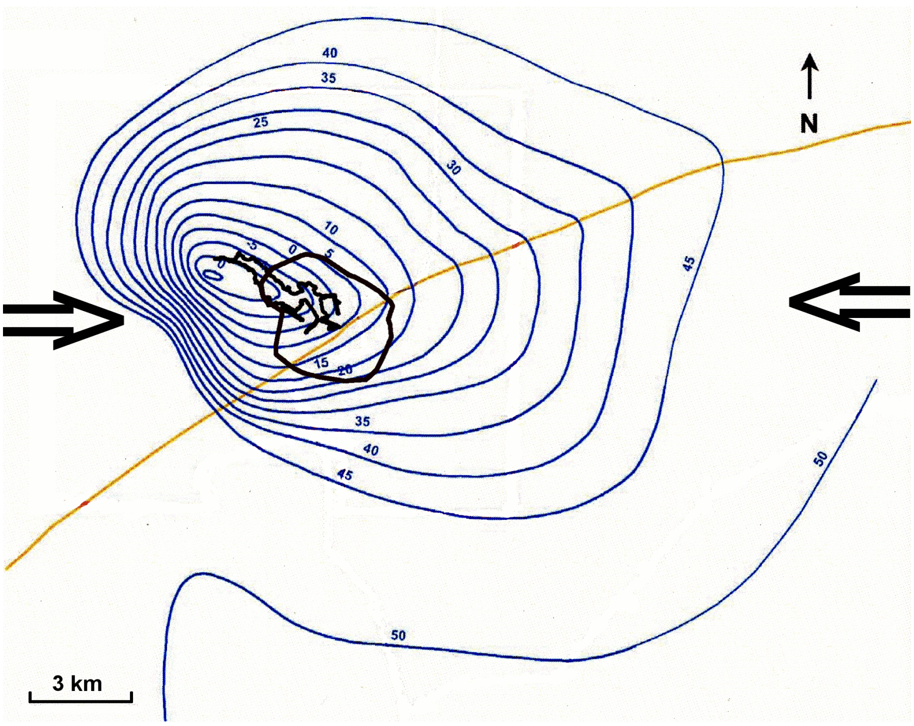

Figure 4 Map of Olympic Dam showing existing underground mine and outline of the proposed open pit in bold black, the potentiometric contours (labeled by elevation, m, above sea-level) in blue, and the trace of the NE-SW Mashers Fault in yellow (the eastern-most 5 km have been truncated). Black arrows indicate the principal horizontal stress direction (Bunger et al. 2008). (modified from 'Figure 6-6', *Appendix K Groundwater and Geochemistry*, ODXdEIS)

Since 1984, to dewater the mine workings, water has been pumped out of the aquifer of the Tent Hill Formation continuously at a rate of 14 to 24 L/s (~1-2 megalitres/day), i.e., a cumulative volume of 10-20 gigalitres at present. As can been seen by the potentiometric contours in Figure 4 which represent data from monitoring wells, this has produced a cone of depression in the aquifer's water table (maximum depression ~ 50 m). Note that the 'geological structure associated with Mashers Fault appears to influence the elongate the [sic] zone of influence along strike to the northeast', indicating that the fault can efficiently transport fluids. Conversely, 'the TSF, located southwest of the underground workings, appears to contribute a source of recharge to the [Tent Hill Formation], which manifests as a steepening of potentiometric contours', i.e., liquid is seeping from the TSF into the aquifer (*Appendix K Groundwater and Geochemistry,* ODXdEIS).

Discussion of the Mashers Fault in the ODXdEIS is confined to its hydrological characteristics – there is no mention of its seismotectonic significance. The overall NE-SW trend of Mashers Fault changes strike by about 11° where the fault crosses the northeast corner of the proposed open pit – the ~10-km-long straight segment to the northeast strikes ~067° (E of N) and the ~10-km-long straight segment to the southwest strikes ~056°. The 100-500-m width of the Mashers Fault at mine site, i.e., the inflexion point, may represent a step-over developed in response to strike-slip movement on the fault. Since the ore body has a relief of ~100 m above the surrounding crystalline basement, the ore body itself may function as an asperity that restricts stick-slip movement on the fault.

Seismotectonic Implications of the Proposed Open Pit Few open pit mines stimulate earthquakes, but, as documented in Table 1, some do. Bunger et al. (2008) report high stresses with an EW direction at 2 km depth near Olympic Dam. The extremely large scale of the proposed mine expansion suggests that some part of the local Earth crustal rock/fluid system will be stressed beyond failure, producing seismicity.

By way of comparison with three open pit mines that have triggered earthquakes (Table 1), note that in terms of its area and depth, 4.1 x 3.5 x 1 km, and its maximum possible unloading stress and pore pressure changes, ~25 and ~10 MPa, respectively, the proposed open pit at Olympic Dam is an order of magnitude greater than the others. Unlike them, because of its great depth, the proposed open pit can also relieve a significant component of the horizontal stress from one side of the Mashers Fault, and thus induce strike-slip failure.

McGarr et al. (2002) infer a logarithmic relation between the linear dimension of the causative engineering activity and the maximum magnitude of the earthquake that can be expected to be caused by that activity. The proposed Olympic Dam open pit has a linear dimension in the range of 1 – 10 km, and their magnitude-length relation would indicate that a maximum possible earthquake in the magnitude range 4 – 6 could occur as a result. Alternately, using the ~25-km maximum diameter of potentiometric contours in Figure 4, an even larger event would be predicted.

The 1968 magnitude 6.9 Meckering earthquake produced an arcuate scarp 35 km long, with a maximum height of 1.8 m, horizontal shortening of 2.2 m, and strike-slip displacement of 1.5 m (Denham et al. 1980; Everingham et al. 1969). The 1986 magnitude 5.8 Marryat Creek earthquake produced a 13-km-long fault scarp with a maximum height of 0.9 m, and the three magnitude 6.3-6.7 1988 magnitude Tennant Creek earthquakes produced two fault scarps with a total length of 32 km and a maximum height of 1.8 m (Crone et al. 1997). Earthquakes that produced comparable scarps at Olympic Dam might cause liquefaction of the saturated surficial deposits and the contents of the TSFs above them, even if the TSFs themselves remained standing. Independent of any strong ground shaking caused by the earthquakes, such scarps would fracture the local geologic structure and might seriously damage the TSFs, causing them to rupture and release their toxic liquid, allowing it to percolate through the fractured surface into the groundwater.

Heavy rains such as the 164 mm recorded in one day on 14 March 1989 at the Roxby Downs Station (Station Number: 016040; BOM 2009) have caused floods in the district (Mainka 1989), and 'the operators [at Olympic Dam] now believed that evaporation ponds were essential … to cope with exceptional circumstances such as the floods of 1989 and 1992' (SA Parliament 1996). Future floods may increase pore pressure in the ground water and trigger seismicity. It is possible that slurry liquefied by an earthquake could be released from damaged TSFs, further distributed over wide areas around the mine by floods, and the fine particles subsequently transported throughout Australia by dust storms (Wikipedia 2009a).

Conclusions The implication of the research reviewed in this paper is that most stable intraplate crust, i.e., the Australian continent, is on the brink of failure by earthquakes, waiting for the proverbial straw that breaks the camel's back. The large, hydrologically potent, and potentially seismogenic Mashers Fault that cuts through the middle of the Olympic Dam ore body poses a significant hazard to the expansion of Olympic Dam, but its seismotectonic significance has apparently been ignored – it needs to be investigated by paleoseismologists and seismologists.

Although there is a wealth of data relevant to the seismotectonic assessment of the Mashers Fault – observations from the existing underground mine, drill cores, local seismograph and/or blast network records, water table records, *in situ* stress and pore pressure measurements, etc. – this information is not available to independent investigators. Enacted by the South Australian Government in 1982, the Roxby Downs Indenture Act provides BHP Billiton (and former mine operator, Western Mining Corporation, WMC) the legal authority to override the Aboriginal Heritage Act 1988, Development Act 1993, Environmental Protection Act 1993, Mining Act 1971, Natural Resources Act 2004, Water Resources Act 1997, and Freedom of Information Act 1991 (Burdon 2006).

An investigation of '“massive leakage of water at Roxby Downs”' by the Parliament of South Australia concluded, 'The Committee is mindful … of the lack of knowledge about what has actually happened to the leaked liquor under Olympic Dam' (Parliament of SA 1996; Note: the figures supplied by WMC that were part of this report have been removed from the online copy). More recently, 'BHP Billiton has declared force majeure on copper and uranium sales from the big Olympic Dam mine in South Australia, where damage from a plummeting ore skip in its main shaft [on 06 October 2009] is expected to reduce capacity to about 20 per cent for up to six months' (Chambers 2009) at a cost of USD$550 million (Williams 2009), but no information about the cause of the accident has been released – the main shaft is ~2 km north-northwest of the surface expression of the Mashers Fault which dips towards it.

With time, the seismogenic potential of the proposed Olympic Dam expansion would increase. The ODXdEIS plan is to turn the pumps off after 40 years and let the open pit fill with water – earthquakes started at Cacoosing Valley five months after the drainage pumps at the quarry were shut off (Seeber et al. 1998). As the open pit filled, the dynamics of reservoir-induced seismicity described by Simpson (2009, 1986) would apply, and the pore pressure would increase in the Mashers Fault, moving it towards failure.

ACKNOWLEDGEMENTS This paper benefited from the editorial suggestions of Kevin McCue and from reviews by him, an anonymous reviewer, and others: Gail Atkinson, Jody Bourgeois, Ben Gardner, Sandra Kanck, Art McGarr, Gavin Mudd, and Rowl Twidale. I have been assisted by many people in preparing both this paper and the antecedent Public Submission, and I thank Dave Boore, Kevin Buzzacott, Ron Dodd, Michael Dwyer, Gary Gibson, Christian Klose, David Love, Vanessa Moio, Robin Mutoid, Irene Nain, Susan Rorsheim, Nano Seeber, Dave Simpson, and Ginny Ward. Inspiration by geologist, Monkey Marc, who changed his act to preserve the Earth and those who live on her.

REFERENCES

Atkinson, G.M. and Boore, D.M. (1995) Ground-Motion Relations for Eastern North America. Bulletin of the Seismological Society of America, Vol 85, No 1, pp 17-30.

BHP Billiton (2009) Olympic Dam Expansion Draft Environmental Impact Statement 2009. BHP Billiton. Retrieved 09MAY2009 < http://www.bhpbilliton.com/bb/odxEis.jsp>.

BOM (2009) Weather Station Data. Retrieved 02NOV2009 < http://www.bom.gov.au/climate/data/weather-data.shtml>

Bowman, J. R. (1992) The 1988 Tennant Creek, Northern Territory, earthquakes: a synthesis. Australian Journal of Earth Sciences, Vol 39, pp 651-669.

Bunger, A., Jeffrey, A.R., Meyer, G., Larking, A., Jenke, G., Klee, G. and Rummel, F. (2008) High horizontal stresses in SE-Australia derived from discing, breakouts and hydraulic fracturing to 2 km depth. 3rd World Stress Map Conference, 15-17 October 2008, Potsdam.

Burdon, P. (2006) Above the law? Roxby Downs and BHP Billiton's Legal Privileges. Friends of the Earth, Adelaide. Retrieved 30OCT2009 < http://www.foe.org.au/anti-nuclear/issues/nfc/mining/roxby/indenture>

Chambers, M. (2009) BHP declares force majeure on Olympic Dam. The Australian, October 21, 2009. Retrieved 03NOV2009 < http://www.theaustralian.news.com.au/business/story/0,28124,26238145-5018061,00.html>

Cranswick, E. (2003) Public Submission on the application licenses for a National Radioactive Waste Repository. Australian Radiation Protection and Nuclear Safety Agency. Retrieved 02NOV2009 < http://cranswick.net/ARPANSA_Submission/index.htm>

Cranswick, E. (2009) Seismicity anticipated to be stimulated by BHP's proposed open pit mine at Olympic Dam. Proposed Olympic Dam Expansion, Public Submissions, Government of South Australia. Retrieved 02NOV2009 < http://www.olympicdameis.sa.gov.au/html/submissions/public/CranswickEdward.pdf>

Crone, A.J., Machette, M.N. and Bowman, J.R. (1997) Episodic nature of earthquake activity in stable continental regions revealed by palaeoseismicity studies of Australian and North American Quaternary faults. Australian Journal of Earth Sciences, Vol 44, pp 203-214.

Crone, A.J., De Martini, P.M., Machette, M.N., Okumura, K. and Prescott, J.R (2003) Paleoseismicity of Two Historically Quiescent Faults in Australia: Implications for Fault Behavior in Stable Continental Regions. Bulletin of the Seismological Society of America, Vol 93, pp 1913–1934.

Denham, D., Alexander, L.G., and Worotnicki, G. (1980) The stress field near sites of the Meckering (1968) and Calingiri (1970) earthquakes, Western Australia. Tectonophysics, Vol 67, pp 283-317.

Environmental Systems & Services, Seismology Centre (2003) Review of Seismicity, Olympic Dam, December 2003.

Everingham, I.B., Gregson, P.J. and Doyle, H.A. (1969) A thrust Fault Scarp in the Western Australian Shield. Nature, Vol 223, pp 701-703.

Knight Piesold Pty Ltd (2004) Olympic Dam Project Tailings Retention System, Investigation into Stability and Maximum Allowable Rate of Rise. Ref 519-49.

Gibowicz, S.J. (1982) Seismicity induced by surface mining: the Belchatow, Poland, earthquake of 29 November 1980. Acta Mont (Czechoslovakia), Vol 61, pp 9-25.

Gibowicz, S.J. (1990) Seismicity induced by mining. Advances in Geophysics, Vol 32, pp. 1-74.

Gibowicz, S.J., Droste, Z., Guterch, B., and Hordejuk, J. (1981) The Belchatow, Poland, earthquakes of 1979 and 1980 induced by surface mining. Engineering Geology Vol 17, pp 257-271.

Hillis, R. R. and Reynolds, S. D. (2003) in situ Stress Field of Australia, Geological Society of Australia Special Publication 22 and Geological Society of America Special Paper 372, pp 49-58.

Mainka, E. (1989) South Australian Floods, Marla area, March 1989. Retrieved 02NOV2009 < http://www.ernmphotography.com/Pages/Weather/89Flood_Gallery/1989FloodingSA.htm>

McCue, K., Barlow, B.C., Denham D., Jones, T., Gibson, G. and Michael-Leiba, M. (1987) Another chip off the old Australian block. EOS, Vol 68, p 609.

McCue, K.F., Wesson, V. and Gibson, G. (1990) The Newcastle, New South Wales, earthquake of 28 December 1989. BMR Journal of Australian Geology and Geophysics, Vol 4, pp 559-568.

McCue, K., Gibson, G., Love, D. and Cranswick, E. (2008) Engineering for earthquakes in Australia. Australian Journal of Structural Engineering, Vol 8, No 1, 1-12.

Mcgarr, A., Simpson, D. and Seeber, L. (2002) Case Histories of Induced and Triggered Seismicity, International Handbook of Earthquake and Engineering Seismology 81A, pp 647–661.

Parliment of SA (1996) Roxby Downs water leakage. Environment, Resources and Development Committee, Parliament of South Australia, Nineteenth report of the Committee. Retrieved 02NOV2009 < http://www.parliament.sa.gov.au/NR/rdonlyres/EC0D12D5-8D47-4C93-9AB1-3726F11D0000/2064/roxbydownsreport.pdf>

Pomeroy, P.W., Simpson, D.W. and Sbar, M.L. (1976) Earthquakes triggered by surface quarrying – the Wappinger Falls, New York sequence of June, 1974. Bulletin of the Seismological Society of America, Vol 66, pp 685-700.

Reynolds, L.J. (2001) Geology of the Olympic Dam Cu–U–Au–Ag–REE deposit. MESA Journal, Vol 23, October 2001, pp 4-10.

Seeber, L., Armsbruster, J.G., Kim, W.-Y. and Barstow, N. (1998) The 1994 Cacoosing Valley earthquakes near Reading, Pennsylvania: A shallow rupture triggered by quarry unloading. Journal of Geophysical Research, Vol 103, pp 24,505-24,521.

Simpson, D.W. (1986). Triggered earthquakes. Annual Review of Earth and Planetary Sciences,Vol.14, pp 21-42.

Simpson, D. (2009) Rapid Changes in Water Level and Reservoir-Induced Seismicity. IASPEI Meeting, Cape Town, January 2009.

Sinadinovski, C., Greenhalgh, S. and Love, D. (2006) Historical earthquakes: a case study for the Adelaide 1954 earthquake. Earthquake engineering in Australia: proceedings of a conference held by the Australian Earthquake Engineering Society / Kevin McCue and Sonja Lenz (eds.), pp 151-158.

Van Loon, A.J. (2002) Soft-sediment deformations in the Kleszczow Graben (central Poland). Sedimentary Geology, Vol 147, pp 57-70.

Wikipedia (2009) 1989 Newcastle earthquake. Retrieved 02NOV2009 < http://en.wikipedia.org/wiki/1989_Newcastle_earthquake>

Wikipedia (2009a) 2009 Australian dust storm. Retrieved 02NOV2009 < http://en.wikipedia.org/wiki/2009_Australian_dust_storm>

Williams, L. (2009) Olympic Dam accident could cost US$550mn in lost copper, uranium, gold and silver output. Mineweb, 21 Oct 2009. Retrieved 03NOV2009 <http://www.mineweb.com/mineweb/view/mineweb/en/page36?oid=91100&sn=Detail>