Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_125

From detonation to discharge: nitrate risks at mine closure

Terry Harck [a,*], David Faulkner [a]

[a] *RGS Environmental Consultants, Australia*

Abstract

The closure of mining operations in arid regions presents significant environmental challenges, particularly concerning the long-term impacts of waste rock landforms on groundwater quality. This paper reviews the process of waste rock seepage generation under arid climate conditions and its role in nitrate contamination of groundwater, focusing on the delayed discharge of nitrate from waste rock landforms after mine closure.

Waste rock landforms, constructed during mining operations, undergo a transitional wetting phase before reaching hydraulic breakthrough, a process that can span decades. During this phase, limited seepage occurs, but once breakthrough is achieved, basal seepage increases significantly, mobilising stored solutes, including nitrate. Nitrate contamination in mining environments is primarily attributed to residues of ammonium nitrate based explosives, which are highly soluble and persist in waste rock for extended periods. Under the arid conditions typical of regions like the Pilbara, nitrate behaves conservatively, with limited attenuation due to the assumed absence of denitrification processes in the predominantly oxic waste rock.

This paper presents a conceptual model of nitrate release from waste rock based on hydrogeochemical modelling and field data from iron ore mining operations in the Pilbara region of Western Australia. It highlights the role of waste rock landforms as key sources of nitrate, with waste rock seepage dynamics controlling the timing and magnitude of nitrate release. The review suggests that nitrate concentrations in groundwater could remain elevated for decades after mine closure, potentially posing risks to groundwater-dependent ecosystems, human users and surface water systems.

The conceptual model is consistent with the spatial and temporally variable concentrations of nitrate observed in monitoring data. However, there remains considerable uncertainty regarding the understanding of seepage dynamics and nitrate transport mechanisms. This is a challenge for mine closure planning. Enhanced monitoring frameworks and targeted studies are needed to quantify nitrate mass loading, and identify and mitigate long-term environmental risks.

Keywords: *waste rock, nitrate, seepage dynamics*

1 Introduction

Mine closure planning increasingly requires robust prediction of post-closure water quality to support regulatory approvals and long-term environmental risk management. In jurisdictions such as Western Australia, closure and environmental approval frameworks (e.g. mine closure plans, Part V approvals under the *Environmental Protection Act 1986*) require proponents to demonstrate that waste rock landforms will not pose unacceptable water quality risks to downstream receptors. This requires prediction of seepage dynamics and hydrogeochemical processes over timescales of hundreds of years.

Nitrate (NO_3) is a water quality parameter that is frequently included in water quality analyses. Nitrate may originate from both natural and mining-related sources, including blasting residues, waste water disposal, tailings facilities and ore processing activities. Many Pilbara iron ore operations have recorded nitrate concentrations in groundwater monitoring bores that exceed site-specific and published guidelines. Our (unpublished) review of ~5,000 nitrate concentrations across ~1,100 locations on 3 Pilbara mine sites

* Corresponding author. Email address: terry@rgsenv.com

indicates that elevated nitrate concentrations are uncommon, with about 90% of nitrate measurements less than 20 mg/L as N (Figure 1). The higher concentrations are confined to a small number of locations. When compared across aquifers, median concentrations are generally below guideline reference values. This suggests that exceedances are driven by localised anomalies rather than broad-scale aquifer degradation.

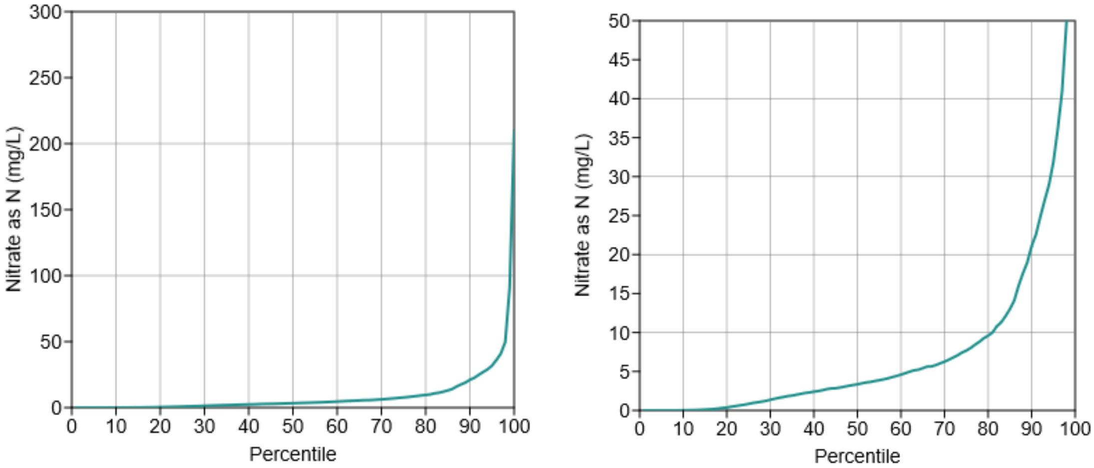

Figure 1 Distribution of nitrate concentrations in groundwater across 3 Pilbara mine sites (same distribution with reduced y scale in right hand plot)

This paper presents a conceptual model that offers a potential explanation of the features of nitrate occurrence observed at Pilbara mine sites. The conceptual model is based on a synthesis of previously published seepage dynamics of waste rock piles (e.g. Williams 2008; Williams & Rohde 2008) and observations of nitrate occurrence on mine sites.

While uncertainties remain, the conceptual model and published studies (e.g. Navarro-Valdivia et al. 2023) suggest that elevated nitrate concentrations from waste rock landform sources may be observed post closure.

2 Methodology

Published literature was reviewed to synthesise current understanding of nitrate on mine sites across all climate conditions but with particular reference to the Pilbara. Search terms included ‘nitrate’, ‘groundwater’ and ‘mine site’ in various combinations on various platforms, including Google and ChatGPT. Similarly, published literature was reviewed to indicate current understanding of seepage dynamics in waste rock landforms. Search terms included ‘waste rock’, ‘seepage’ and ‘moisture’ in various combinations on various platforms, including Google and ChatGPT. Characteristics of nitrate monitoring data from 6 Pilbara mine sites were synthesised from the authors experience. The information was integrated into a conceptual model.

3 Results

The topic is not widely assessed. Search results yielded 11 papers of relevance, most of which are referenced in this paper.

3.1 Mine site nitrate

Nitrate (NO_3^-) is a naturally occurring ion in soil and groundwater, derived primarily from the oxidation of organic nitrogen and ammonium under aerobic conditions. In arid and semi-arid regions such as the Pilbara, natural background concentrations of nitrate are generally low due to limited organic matter and biological cycling. However, local enrichment can occur due to biological activity.

The Western Australia Department of Water (2016) assessment of valley-fill and channel iron deposit aquifers in the northwest Hamersley Range reported nitrate concentrations usually below 1.1 mg/L NO_3-N, indicating that naturally occurring nitrate in undisturbed aquifers of the Pilbara is low. Similarly, hydrogeochemical mapping by Gray et al. (2019) suggests that background nitrate concentrations across the Pilbara are typically below 5 mg/L NO_3-N. However, the mapping also shows higher concentrations – in the 30–60 mg/L NO_3-N range.

Localised enrichment can occur through biological nitrogen fixation and oxidation of ammonium in soil profiles, particularly where cyanobacterial soil crusts or termite mounds are present. This mechanism has been recognised as a natural source of nitrate in Western Australian groundwater, with concentrations occasionally reaching up to 80 mg/L NO_3-N in shallow systems (Rajapakse et al. 2019). Concentrations up to 7 mg/L NO_3-N are reported from the Millstream aquifer, a dolomite aquifer located in the central Pilbara (Barnett & Commander 1985). Such occurrences may be spatially limited but highlight the importance of considering regional variability when interpreting site-specific investigation results.

3.2 Explosive residue

In modern mining operations, the dominant anthropogenic source of nitrate contamination is incomplete detonation or spillage of ammonium nitrate-based explosives, particularly ammonium nitrate fuel oil (ANFO). The nitrogen in ANFO is highly soluble, and undetonated residues can leach rapidly through waste rock or exposed pit surfaces upon contact with infiltrating rainfall (Gemson et al. 2022).

Numerous studies have quantified nitrate concentrations arising from blast residues in waste rock and mine drainage. Research by Hendry et al. (2018) and Mahmood (2016) demonstrated that nitrate derived from ANFO exhibits a distinctive isotopic signature and can dominate the nitrogen load within mine waste rock. Porewater concentrations in freshly blasted waste rock may range from 5 to 100 mg/L NO_3-N, with mean concentrations of approximately 144 mg/L NO_3-N decreasing to 48 mg/L NO_3-N in aged material due to flushing by meteoric water. These studies were carried out on sites in British Columbia, Canada, where annual precipitation is about 600 mm, at least twice the Pilbara average. Extreme nitrate cases have been reported in mine effluent and seepage, including concentrations up to 2,000 mg/L NO_3-N at diamond mines and 60–80 mg/L NO_3-N at uranium mines (Hendry et al. 2018).

Mahmood (2016) confirmed through isotopic analyses ($\delta^{15}N$ and $\delta^{18}O$) that the source of nitrate in waste rock is overwhelmingly derived from explosive residues. The study indicated more than 80% of measured nitrate was produced via nitrification of ammonium originating from undetonated ANFO.

3.3 Nitrate in mine water

Elevated nitrate concentrations have been documented in mine-affected groundwater across the Pilbara. For example, Roy Hill reported spatially variable nitrate levels, with concentrations up to 4.5 mg/L NO_3-N on the tenement periphery and 10 mg/L NO_3-N in the central mining areas, consistent with diffuse nitrate inputs from blasting and ore handling (Roy Hill Iron Ore Pty Ltd 2025). The Gemson et al. (2022) meta-analysis found that groundwater nitrate concentrations attributable to mine influence typically range from 1.5 to 60 mg/L NO_3-N, substantially higher than background levels, which they considered <1 mg/L NO_3-N at 10 sites across the globe.

Surface water bodies in mining areas, such as pit lakes, waste rock drainage or ephemeral creek systems, may also become enriched in nitrate where run-off interacts with blast residues or infiltrates through impacted waste rock. Given the high solubility and mobility of nitrate under oxic conditions, such contamination can propagate beyond the mine footprint, particularly during high rainfall events, although attenuation may occur via dilution or denitrification in organic-rich sediments.

3.4 Nitrate attenuation

The potential for denitrification processes may theoretically occur in sub-oxic to anoxic zones within waste rock dumps, attenuating nitrate concentrations. Microbial denitrification has a characteristic isotope signature. The lighter ^{14}N is transferred to N_2, resulting in enrichment of the heavier isotopes ^{15}N and ^{18}O in the remaining NO_3 (Mahmood 2016). Isotopic studies of coal mine waste rock suggest limited occurrence of denitrification in unsaturated waste rock although it is clearly identified in saturated waste rock (Hendry et al. 2018; Mahmood 2016). It is not clear whether denitrification is likely in Pilbara waste rock and this is an area of investigation. If conditions remain oxidising in Pilbara waste rock, then nitrate will not be attenuated and its high solubility should make it readily leachable, potentially increasing local groundwater nitrate concentrations.

Field observations highlight that leaching efficiency is scale-dependent: small-scale laboratory experiments underestimate nitrate flushing compared with field-scale dumps, where up to 80% of the initial nitrate mass can be removed over several decades under high rainfall conditions (Mahmood 2016). This implies that nitrate derived from blast residues can persist in waste rock for prolonged periods following deposition. Then the release of nitrate from a waste rock landform source may be largely controlled by the physical processes that control seepage.

3.5 Waste rock seepage dynamics

When a waste rock landform is first constructed, the waste rock is typically very dry, with large air-filled voids between particles and minimal moisture except from occasional rainfall events (Williams 2006). This unsaturated zone extends from the top surface of the landform down to the base. In this condition, water movement is generally limited to thin films around particles. Oxygen and water in the void space induce weathering and solute release at the particle surfaces, although mobilisation of the solutes is limited by the restricted water movement.

Some seepage may flow laterally along lower permeability zones (such as trafficked surfaces). However, most water infiltrating the top surface of the landform is expected to percolate downward. As infiltration occurs, primarily from intense rainfall events which exceed evaporation, the water content at the top of the column increases. A minor proportion of the infiltration may find preferential flow paths through the waste rock and exit as seepage. Most of the infiltration enters the pore space in the top of the waste rock. This moisture forms a wetting front: the advancing boundary between the relatively dry material below and the progressively wetter zone above. It is important to recognise that the concept of extinction depth does not prevent deeper downward movement of moisture in soil-like materials.

As the wetting front, and its mobilised solute load, moves downward, it progressively loses mass (water and solutes) to pore space storage, causing the advancing front to weaken. Initially, wetting fronts do not reach the base of the column. However, as the water content of the pores in the upper portions of the column increases, the depth of penetration of wetting fronts increases.

Repeated infiltration events over time cause the moisture content to increase progressively and wetting fronts driven by significant rainfall events move deeper. Once the degree of saturation in the entire waste rock column reaches about 60% (Williams 2008), the system shifts from discontinuous to continuous. This point is known as continuum breakthrough, and is characterised by:

- Hydraulic conductivity increases by several orders of magnitude.
- Water, with its solute load, starts to drain gravitationally through the waste rock.
- Seepage from the base of the waste rock is controlled mainly by the rate of infiltration through the top surface.

There may be an extensive lag time (years or decades) before a landform reaches breakthrough.

Continuum breakthrough allows greater solute mobilisation and transport, as more porewater becomes available to dissolve and move reaction products (e.g. nitrate, sulphate, metals). Chemical weathering reactions also tend to accelerate once sufficient moisture is present to sustain microbial and geochemical processes.

The period before continuum breakthrough represents a transitional phase during which moisture accumulates within the waste rock before significant seepage (with its solute load) occurs. Note that minor seepage occurs during the transition phase from limited infiltration along preferential flow paths (if they exist).

Prior to breakthrough, rainfall infiltration goes to the broad-scale increase in dump saturation with a minor component (about 2–4% of annual rainfall) following preferential flow paths and emerging as base seepage (Williams 2008). After breakthrough, seepage ranges from 2% to 85% of average annual rainfall, with an average of 37%, based on a trial at Cadia in New South Wales, and reported data from 3 other Australian sites and 4 sites in the Americas (Williams & Rohde 2008).

The rate and depth of wetting depend on factors such as material texture, compaction, permeability contrasts and antecedent moisture content. Estimates of the duration of the transitional phase range from 10 years, for a pile height of 15 m, to over 120 years, for a height of 120 m, for an annual rainfall of ~300 mm (Williams 2008). Annual rainfall for the Pilbara is about 250–350 mm.

3.6 Nitrate monitoring

Our experience reveals common challenges in the evaluation of site monitoring data, of nitrate in particular (Table 1).

Table 1 Monitoring limitations

Category	Limitations
Monitoring network	Thera are insufficient monitoring locations suitable for assessment of linkages from landforms to groundwater, e.g. within cones of depression caused by dewatering. Uncertainty between the depth of pits and the aquifers likely to be affected means proximal bores may not be screened in the appropriate aquifer. Many historical monitoring locations have limited monitoring records and/or are defunct. Bore construction records are incomplete or absent.
Monitoring data quality	Monitoring is too infrequent to correlate with events of interest, e.g. rainfall, pit backfilling, landform development, etc. Analytical data are limited, with parameters of interest absent or incomplete, preventing internal consistency checks.

Considering the above, reasons for the lack of elevated nitrate in locations where it would be expected include:

- There is a lack of recent monitoring. Therefore, updated sampling may confirm the lack of a linkage to a nitrate source.
- The understanding of the hydrogeology and/or effects of dewatering is incomplete.
- There are possible bore construction issues or incorrect understanding of bore construction specification.
- The assumed nitrate source is not producing enough soluble nitrate to produce a measurable impact.
- The transitional period prior to continuum breakthrough (‘wetting up’ period) is underway and no linkage to the source is in place yet.

Our experience is that monitoring networks are frequently not optimised to make the connection between likely sources of nitrate and groundwater. This is because most scrutiny is aimed at monitoring dewatering/injection systems, which directly affect mining operations and require annual reporting under the *Rights in Water and Irrigation Act 1914* (Government of Western Australia 1914). Environmental water quality monitoring is less operationally critical.

3.7 Implications for Pilbara mine site nitrate

At Pilbara operations, nitrate occurrence should be interpreted within a framework recognising low natural background levels (<5 mg/L NO_3-N) and the potential for significantly higher concentrations (tens to hundreds of mg/L NO_3-N) arising from explosive residues and subsequent leaching from waste rock or mine infrastructure. Table 2 summarises the seepage implications.

Table 2 Characteristics of Pilbara waste rock seepage over time

Timeframe	Basal seepage	Toe seepage
Short term (during operations, potentially extending into closure)	May be too small to have observable effects in groundwater levels and quality (pre-breakthrough period)	May occur after significant rainfall events, combining the contributions from preferential flow paths (if they exist) and run-off from the exterior of the landform
Long term (after mine closure)	May increase by orders of magnitude compared to short term and may be observable in groundwater levels and quality (post-breakthrough period)	May be frequent after significant rainfall events

Since nitrate is extremely soluble, its rate of release will be controlled by how rapidly seepage emanates from the waste rock source. Waste rock seepage dynamics are controlled by factors such as particle size, porosity, landform thickness (height) and rainfall variability (Williams 2006; Williams 2008; Williams & Rohde 2008).

4 Discussion

Based on the results presented above, it may be concluded that natural background nitrate levels in the Pilbara are low, with scattered biogenic 'hot spots'. Mining activities represent a plausible and well-documented source, supported by the spatial clustering of monitored nitrate exceedances near operational infrastructure and landforms. Although no single definitive ('smoking gun') source can be readily identified, the weight of evidence points toward mining-related influences, particularly waste rock landforms.

Waste rock, produced from stripping, blasting and excavation, is heterogeneous in size, geology, mineralogy and nitrate content. Rainfall infiltrates or runs off the pile, mobilising solutes such as nitrate. Run-off may be captured by local surface water management infrastructure, adjacent mine pits or natural drainages. Seepage can infiltrate the underlying ground or be diverted laterally along conductivity contrasts, discharging at the landform toe. Toe seepage (if it occurs) is likely to report to the same pathways as run-off.

Under Pilbara average rainfall conditions, landforms several tens of metres high would take decades to 'wet up'. Therefore, some landforms at some mining operations, may not yet be producing significant seepage. Since the majority of nitrate is flushed from waste rock during displacement of the first pore volume (Mahmood 2016), there may yet be a significant mass of nitrate available for mobilisation within Pilbara waste rock landforms.

If waste rock backfilling is conducted before significant seepage occurs, then the nitrate load in the waste rock will also be transferred into the pit (although there may be losses during the transfer process, for example, through rainfall flushing). The nitrate load in waste rock below the long-term pit water level can potentially be mobilised by groundwater through-flow once groundwater levels recover. Waste rock deposited in-pit will range from oxidising conditions near surface to reducing and saturated conditions with depth. While oxidising conditions will make nitrate the stable form of nitrogen, reducing conditions may encourage denitrification, potentially reducing nitrate concentrations.

5 Conclusion

This review demonstrates that elevated nitrate concentrations observed at Pilbara mine sites are unlikely to be attributable to natural background sources and are more plausibly linked to mining-related activities, particularly the emplacement and long-term hydraulic evolution of waste rock landforms. Natural nitrate concentrations in Pilbara groundwater are typically low, whereas ammonium nitrate based blasting residues provide a large, highly soluble and persistent nitrogen source capable of generating concentrations orders of magnitude higher than background levels.

Although nitrate is commonly regarded as readily flushed from mine waste, the evidence reviewed here indicates that its mobilisation is strongly governed by landform seepage dynamics rather than solubility alone. In arid environments, waste rock landforms may remain in a prolonged transitional wetting phase for decades, during which nitrate is mobilised slowly and only minor seepage occurs. However, once continuum breakthrough is achieved, basal seepage rates can increase substantially, allowing for delayed but potentially significant nitrate discharge to groundwater and surface water systems long after mine closure.

This conceptual framework provides a plausible explanation for the spatially limited yet sometimes persistent nitrate exceedances observed at Pilbara operations, as well as for the absence of widespread impacts during the operational life of many mines. It also highlights that the absence of current exceedances does not necessarily imply a negligible long-term risk, particularly for large waste rock landforms that have not yet reached hydraulic breakthrough.

The findings emphasise the importance of designing mine closure strategies and monitoring programs that can manage and observe long-term seepage evolution and solute flushing processes. Monitoring networks should be optimised to test upstream and downstream nitrate concentrations over appropriate spatial and temporal scales. Closure risk assessments should incorporate the potential for delayed nitrate release following mine closure and/or groundwater recovery. The potential for denitrification in the cores of large waste rock landforms is a topic for further research.

In conclusion, understanding the transition from detonation-derived nitrate storage in waste rock to eventual discharge via seepage is essential for credible water quality risk assessments and sustainable mine closure outcomes in arid climates.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used ChatGPT, Gemini and Copilot to conduct searches for relevant published information and improve the language and clarity of writing. The authors have reviewed the content and edited it where required and take full responsibility for said content.

References

Barnett, J & Commander, D 1985, *Hydrogeology of the Western Fortescue Valley, Pilbara Region, Western Australia*, Geological Survey of Western Australia, Perth.

Department of Water 2016, *Groundwater Assessment of the North-West Hamersley Range*, Perth.

Gemson, W, Harck, T & Burgess, R 2022,'Nitrate dynamics at mine sites – broader context, source and management considerations', in J Pope, C Wolkersdorfer, R Rait, D Trumm, H Christenson, K Wolkersdorfer (eds) *IMWA 2022 Conference – "Reconnect"*, International Mine Water Association, Christchurch, p. 590.

Government of Western Australia 1914, *Rights in Water and Irrigation Act 1914*.

Gray, D, Reid, N, Noble, R & Giblin, A 2019, *Hydrogeochemical Mapping of the Australian Continent*, CSIRO Mineral Resources, Perth.

Hendry, MJ, Wassenaar, LI, Barbour, SL, Schabert, MS, Birkham, TK, Fedec, T, & Schmeling, EE 2018, 'Assessing the fate of explosives derived nitrate in mine waste rock dumps using the stable isotopes of oxygen and nitrogen', *Science of The Total Environment*, vol. 640–641, pp. 127–137.

Mahmood, FN 2016, *Nitrate In Coal Waste Rock Dumps, Elk Valley, British Columbia, Canada*, MSc thesis, University of Saskatchewan, Saskatoon.

Navarro-Valdivia, L, Weber, PA, Tuck, J, & Hillman, C 2023, 'Natural Decay of ANFO-derived nitrate in pit lakes: insights from the Golden Bar Pit Lake, Macraes Gold Mine, Otago, New Zealand', AusIMM New Zealand Branch Annual Conference 2023, viewed 22 August 2023, https://www.ausimm.com/globalassets/communities/branches/nz-branch/2023-conference-presentations--abstracts/navarro_natural-decay-of-anfo-derived-nitrate-in-pit-lakes.pdf

Rajapakse, J, Rainer-Smith, S, Millar, GJ, Grace, P, Hutton, A, Hoy, W, Jeffries-Stokes, C, & Hudson, B 2019, 'Unsafe drinking water quality in remote Western Australian Aboriginal communities', *Geographical Research*, vol. 57, no. 2, pp. 178–188.

Roy Hill Iron Ore Pty Ltd 2025. *Appendix 02: Life of Mine Water Management Strategy, Supporting Document to the Revised Proposal for the Roy Hill Iron Ore Mine*, Environmental Protection Authority Western Australia, Perth, https://www.epa.wa.gov.au/proposals/revised-proposal-roy-hill-iron-ore-mine

Williams, DJ 2006, 'Mine Closure as a Driver for Waste Rock Dump Construction', in AB Fourie & M Tibbett (eds), *Mine Closure 2006: Proceedings of the First International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 697–706, https://doi.org/10.36487/ACG_repo/605_61

Williams, DJ 2008, 'The influence of climate on seepage from mine waste storages during deposition and post-closure', in AB Fourie, M Tibbett, I Weiersbye & P Dye (eds), *Mine Closure 2008: Proceedings of the Third International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 461–473, https://doi.org/10.36487/ACG_repo/852_42

Williams, DJ & Rohde, TK 2008, 'Rainfall Infiltration Into and Seepage From Rock Dumps — A Review', in AB Fourie (ed.), *Rock Dumps 2008: Proceedings of the First International Seminar on the Management of Rock Dumps, Stockpiles and Heap Leach Pads*, Australian Centre for Geomechanics, Perth, pp. 79–89, https://doi.org/10.36487/ACG_repo/802_7