SSIM 2023 – PM Dight (ed.)
© 2023 Australian Centre for Geomechanics, Perth, ISSN 3083-399X
doi:10.36487/ACG_repo/2335_28

Geotechnical slope design in hard rock lithium deposits

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Abstract

The increasing demand for commodities such as lithium is driven by the accelerating transition to a green economy. Currently, there are two primary types of lithium mines: brine and hard rock or, more specifically, pegmatite (spodumene) deposits. This paper synthesises the geotechnical controls on slope design and the associated risks for hard rock lithium deposits. Typical controls are illustrated, using specific examples from recent experience at three lithium deposits and operations in Australia and Africa.

Geological models of hard rock lithium deposits comprise the pegmatite orebody and the surrounding country rocks. The orebody is typically an inclined pegmatitic intrusion, creating a footwall and hanging wall open pit setting. The country rocks vary in the degree of metamorphism of sedimentary and igneous protoliths. Weathered or transported material up to a 5–60 m depth may pose localised geotechnical risks.

Fresh rock mass conditions are typically favourable with high intact strengths. This means that the structural geology is critical to geotechnical slope design. For hard rock lithium deposits, key elements of the structure model are:

- *Orientation of pegmatite intrusions and potential shearing at the contacts with country rocks.*
- *Presence of foliation or bedding.*
- *Regional scale faults and shears.*

Geotechnical conditions on the hanging wall are typically favourable for slope design, while the footwall interacts with potentially unfavourable structural conditions where careful geotechnical design is required. Slope stability risks are typically bench to multi-bench scale issues. Examples of common risks, stability issues and techniques for managing them are presented in this paper.

Keywords: *lithium, geotechnical slope design, pegmatite*

1 Introduction

On a global scale, lithium is extracted from two primary sources: brines and minerals. Lithium extracted from brines primarily comes from continental brine deposits located in countries such as Chile, Argentina and Bolivia (Figure 1). Lithium has also been successfully extracted from oilfield and geothermal brines, suggesting that these unconventional sources may become important contributors to lithium production in the future. At present, the extraction of lithium-bearing minerals, such as spodumene and petalite, is primarily conducted in Australia, Africa and Brazil, with pegmatites being the main source (Figure 1). As we look to the future, additional lithium minerals are likely to emerge, including hectorite and jadarite, which are found in certain sedimentary basins.

Spodumene is the principally mined lithium-bearing mineral due to its high lithium content. It occurs within pegmatites, which are very coarse-grained igneous rocks, understood to result from the crystallisation of melts. Lithium-rich pegmatites include the important lithium-caesium-tantalum (LCT) pegmatite family, highly peralkaline varieties and the metasomatic deposits associated with pegmatites.

Figure 1 Global lithium mines, deposits and occurrences, November 2021 (after Shaw 2021)

Lithium pegmatites are typically intruded during later stages of tectonic activity related to plate convergence (Phelps-Barber et al. 2022). In these settings, the pegmatites may be emplaced during deformation and regional metamorphism or after these events (Bradley et al. 2010). Pegmatite fluids typically originate from S or I type granite plutons and fluids transported along regional structures. Hence, pegmatite emplacement is commonly structurally controlled by large-scale shear zones or faults. However, there are few detailed studies on structural controls for individual deposits. Exceptions to this are the Greenbushes deposit in the Yilgarn Craton (Partington 1990; Partington et al. 1995; Partington 2017) and the Pilgangoora deposit in the Pilbara Craton (Sweetapple & Collins 2002). With these deposits, both compressional and extensional regimes controlled the complex geometry of the pegmatites.

While pegmatite lithium deposits account for less than 40% of the known resources, they represent about 60% of lithium production globally (Bowell et al. 2010). This paper looks at the geotechnical ground conditions typically encountered with these deposits and the controls on slope design. These conditions are illustrated through examples from three case study sites: two in Australia and one in Africa.

2 Geotechnical model: geology

Lithium pegmatite deposits in Australia are typically located in greenstone belts (Phelps-Barber et al. 2022), some with associated granite intrusions. All occur in relatively competent regionally metamorphosed host rocks of upper greenschist to amphibolite facies. Although spatial associations with parent granite intrusions are stressed in the literature, there are no obvious consistent spatial relationships for deposits identified in Western Australia.

Spodumene is the major lithium mineral currently mined within Australia. It typically occurs within gently dipping pegmatitic swarms, which is consistent with characteristics of spodumene pegmatites globally. A comparison of Australian and global LCT pegmatite deposits is provided in Table 1, based on publicly available data and literature. In particular, the table compares the typical pegmatite dip and metamorphic grade of the surrounding country rock.

Table 1 Comparison of global LCT spodumene pegmatites

Country	Deposit	Pegmatite dip	Country rock metamorphic grade	Reference
Australia	Greenbushes	Gentle	Amphibolite	Partington (2017)
	Pilgangoora	Gentle	Amphibolite	Sweetapple et al. (2017)
	Earl Grey	Gentle	Amphibolite	Phelps-Barber et al. (2022)
	Mount Marion	Sub-horizontal	Lower amphibolite	Smith & Ross (2017)
	Buldania (Anna)	Sub-horizontal to steep	Amphibolite	Liontown Resources (2023) ASX release
	Bynoe Pegmatite Field	Gentle to steep	Greenschist	Rawlings (2017)
DRC*	Manono	Sub-horizontal	Amphibolite	AVZ Minerals (2023)
Zimbabwe	Bikita	Gentle	Lower amphibolite	Bradley et al. (2010)
Ethiopia	Kenticha	Sub-horizontal	Amphibolite	Küster et al. (2009)
China	Jiajika	Gentle to steep	Lower amphibolite	Huang et al. (2020)
Portugal	Mina do Barroso	Gentle	Lower amphibolite	Savannah Resources (2023)
Canada	Whabouchi	Gentle	Amphibolite	Nemaska Lithium (2023)

*DRC = Democratic Republic of the Congo

The broadly syn-metamorphic timing of the intrusion allows the pegmatites to cool slowly, enabling greater fractionation and concentration of volatiles and elements like lithium. The typically gentle dip of the pegmatites in a syn-kinematic environment with vertical extension allows progressive inflation and growth of the lithium-enriched pegmatites. The resultant pegmatites are thus enriched with not only lithium but also geometry suitable for open pit mining over extensive strike lengths. However, there are also examples of pegmatite fields with stacked pegmatite bodies that range from gently to steeply dipping. Cross-sections through two pegmatite bodies, one gently dipping and one steeply, at two Australian case study sites are shown in Figure 2.

The dimensions and shape of the pegmatite deposits are dependent upon the competency of the host rock (Phelps-Barber et al. 2022). Pegmatite dykes emplaced in competent rocks such as metabasalts, gneiss and amphibolite typically form planar and extensive bodies.

The geological similarities of the spodumene pegmatites in Australia and globally allow general conclusions about common geological slope design considerations. Key geological features influencing slope design are:

- Shape and inclination of the pegmatite intrusion (steeply to shallowly inclined). This will influence pit shape and whether pit development will include a footwall/hanging wall arrangement or two hanging walls (Figure 2).
- Single intrusion or a stacked series of pegmatitic intrusions of varying dip.
- Depth of weathering, which can vary from a relatively thin skin of 5 m up to 60 m thick. This is discussed further in the following section.

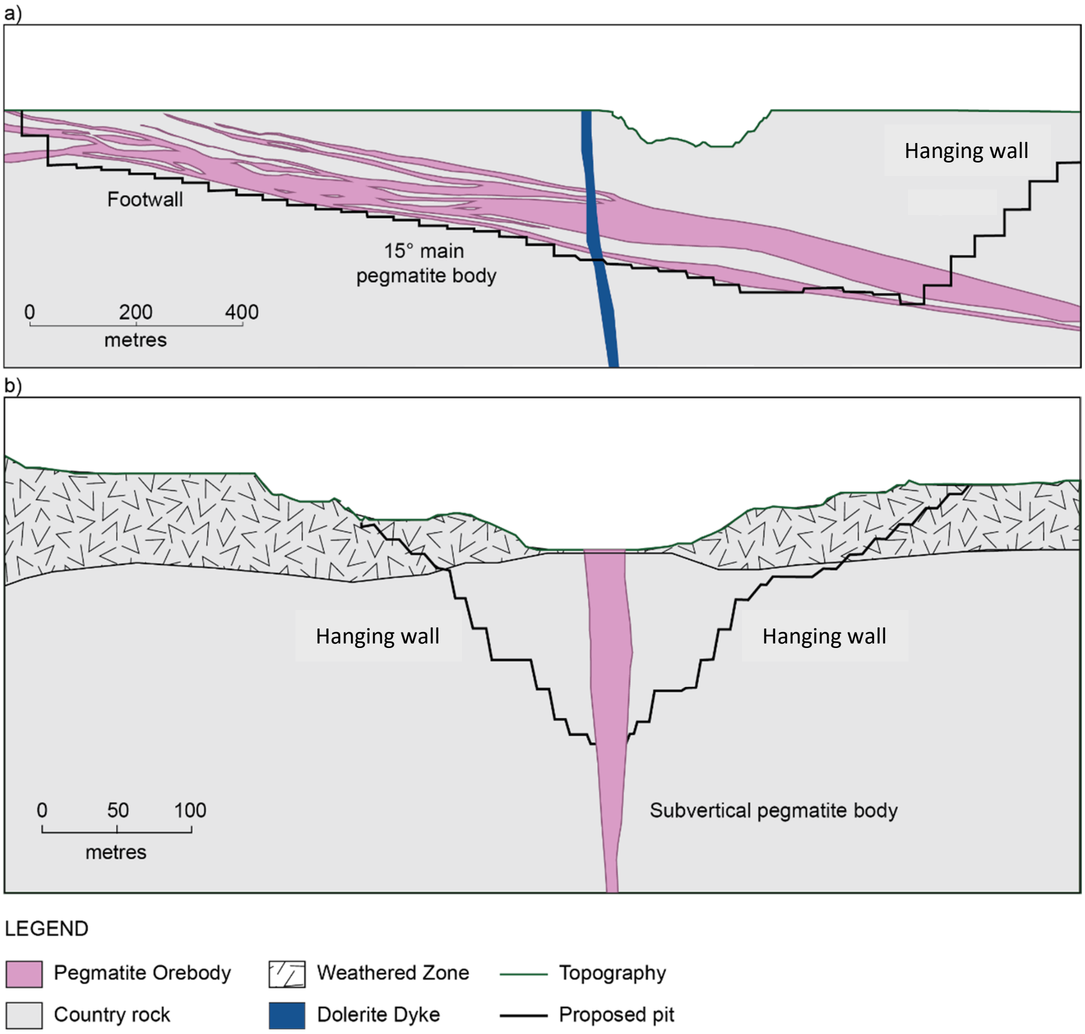

Figure 2 Cross-sections through two case study sites. (a) Gently dipping pegmatite body; (b) Steep pegmatite body

3 Geotechnical model: rock mass

Rock mass conditions are controlled by the geology and surface processes at the site. The rock mass units typically comprise:

- Weathered zone: extremely weathered in situ rocks, residual soils and transported soils; soil to very low intact rock strength.
- Transitional zone: increased intact rock mass strength, weathering along discontinuities.
- Fresh high-strength rock: at least two rock mass units, pegmatite and metamorphosed country rock.

The transition from weathered rock to fresh is relatively sharp at most sites; however, in some cases a secondary weathered or transitional zone is also present. Example strengths for the weathered and transitional zones from two case study sites are provided in Table 2.

Table 2 Comparison of weathered zone strengths

Case study site	Rock mass unit	Approximate thickness (m)	Mohr–Coulomb parameters	
			Cohesion (kPa)	Friction angle (°)
Site A	Upper weathered	50–60	30	24
	Transitional	10–20	80	28
Site B	Upper weathered	10–30	20	30
	Transitional	0–10	100	30

The fresh rock for both the pegmatite and the country rock typically has a high intact strength (>100 megapascals [MPa]). The main differentiator between units (besides lithology) is foliation in the country rock, which may impact the overall rock mass strength. The presence of foliation can result in a strong strength anisotropy for the country rock, particularly for those with a sedimentary protolith. The anisotropy can make assessment of intact strength difficult, and sample selection for testing requires careful consideration. Rock mass strengths from two case study sites are provided in Table 3. Given the high rock mass strengths in fresh rock, an understanding of the geological structures is an important component of the geotechnical model.

Table 3 Comparison of fresh rock mass strengths

Case study site	Rock mass unit	Intact strength (MPa)			GSI*	m_i
		Minimum	Maximum	Mean		
Site A	Pegmatite	90	200	120	60 –77	20
	Metasediment	40	170	100	55–70	10
Site B	Pegmatite	60	180	125	63–70	19
	Amphibolite	85	300	170	65–79	15
	Granofels	62	160	90	65–70	15

*GSI = geological strength index

4 Geotechnical model: structure

The structural geology is critical to the geotechnical slope design for LCT pegmatite deposits. Here the structural geology model is referring to both major structures (i.e. faults and shears) as well as the structural fabric (i.e. foliation and jointing patterns). The structure model is again strongly controlled by the pegmatite body, both in terms of major structures and fabric.

Cooling joints associated with a decrease in volume are created from tensional stresses within an igneous body. The volume decrease is due to thermal contraction through cooling of the body. Cooling related joints are oriented perpendicular and parallel to the dip of the dyke due to heat flow. This is shown conceptually in section in Figure 3a. Cooling joints are not as well developed in pegmatites compared with say thin basaltic dykes as the pegmatite has cooled over substantially greater time frames.

Tectonic joints are those joints that develop, post pegmatite formation due to ongoing deformation of the region. The tectonic joints will have similar orientations in both the pegmatite and country rock. Cooling joints can be difficult to differentiate from tectonic joints (Rabbel et al. 2021). Contact fractures also develop due to mechanical stress that built up while the magma or lava cooled and contracted (Hetenyi et al. 2012).

Two stereographs from Case Study Site A are presented in Figure 3. The stereographs show structures measured from the oriented core of five boreholes through both pegmatite and the country rock. The pegmatite at the site is sub-vertical and striking north-northeast. The pegmatite stereograph (Figure 3b) shows shallowly dipping joints, oriented perpendicular to and parallel with the pegmatite body, which are interpreted as cooling and contact joints, respectively. Some of the jointing is of similar orientation to the metasedimentary country rock (Figure 3c) and therefore may also be tectonic joints.

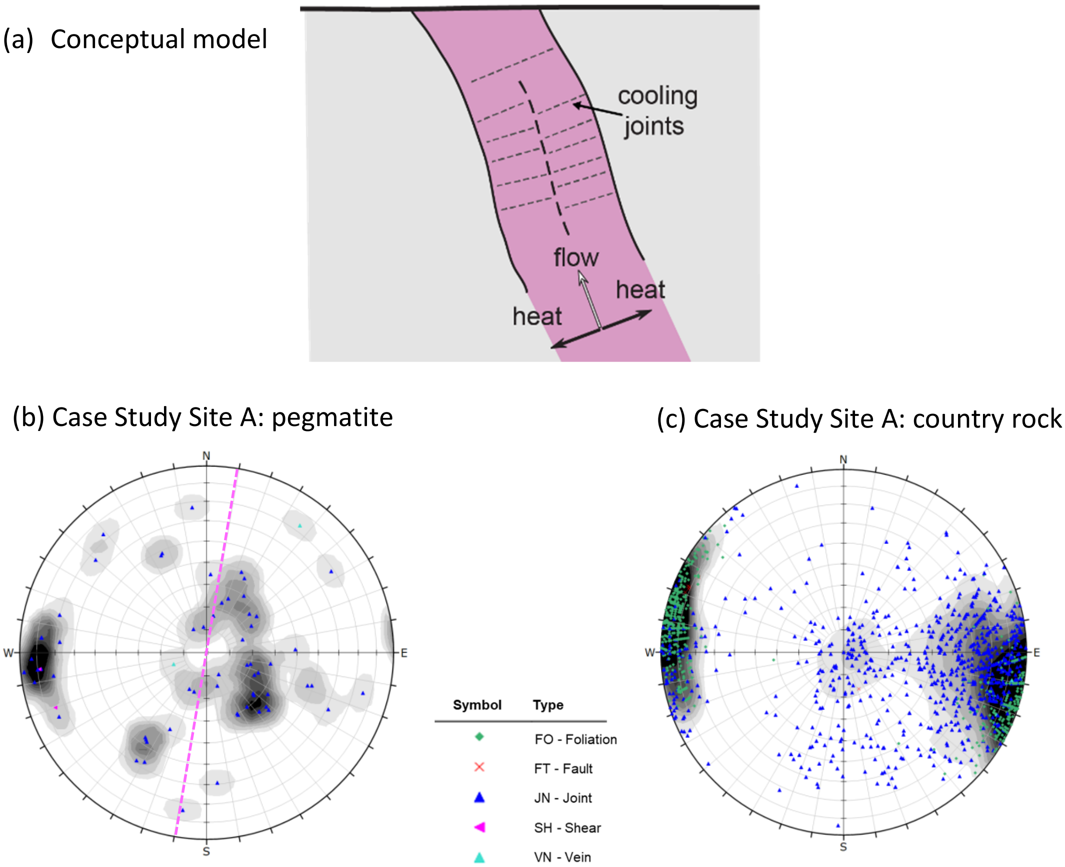

Figure 3 Pegmatite jointing patterns. (a) Conceptual model of thermal (cooling) joints, and example structure conditions at Case Study Site A with stereographs from oriented core for (b) pegmatite and (c) metasedimentary country rock. Pink dashed line indicates strike of the pegmatite body. Stereographs are lower hemisphere, equal area

A structural domain is a volume of rock with similar structural patterns and characteristics. At LCT pegmatite deposits, the domains reflect the lithological control on structural patterns. For example, at Case Study Site A the country rock structural patterns are dominated by the sub-vertical foliation and the joint set moderately dipping west (Figure 3). The structural patterns and character are sufficiently different from the pegmatite, so the two structural domains are defined.

In addition to orientation differences, there are inherent differences in defect lengths and terminations, which are also a result of lithological controls. For example, geological structures, such as joints, typically terminate within the pegmatite body or at the contact.

Shearing along the pegmatite contact with country rocks is common at some case study sites. These shears can include:

- Discrete shears along or near the contact.
- Sheared zones that include large intervals of clay gouge and fragmented rock.

Examples of how each of these structures appear in core are shown in Figure 4. The occurrence and extent of the shear contact is significant in slope design, as it can potentially form a large planar sliding mechanism on the footwall.

Figure 4 Examples of shearing at pegmatite contact. (a) Discrete shear; (b) Extensive shear zone with broken zones and clay gouge

In summary, critical controls for structure model and slope design are as follows:

- As distinct lithological units, the different method of formations means an inherent variation in structural patterns and/or defect continuity. Consequently, the pegmatite will form a separate structural domain to the surrounding country rock.
- Foliation is the common structure type in the metamorphic country rock. Foliation can form pervasive, continuous defects or a fabric.
- Joints are likely to terminate at the contact between the pegmatite and the country rock.
- Major structures can parallel the pegmatite bodies.

5 Geotechnical model: hydrogeology

Hydrogeological conditions for pegmatite deposits are controlled by a low transmissivity fractured rock mass. The pegmatite body itself typically compartmentalises pore pressures. This is interpreted as being largely due to the termination of structures at the contact. Weathered zones have enhanced transmissivity, as do strike-parallel and transverse contacts and shear zones on pegmatite and faults. The low transmissivity rock masses drive:

- Comparatively high pore pressures and steep hydraulic gradients behind the pit walls.
- Comparatively low groundwater inflows, which favour sump pumping for groundwater control rather than production bores; hence, pit dewatering is typically concurrent with and not in advance of mining.
- Recharge from rainfall and slow drainage contributes to soft ground conditions for traffic across benches.

6 Slope design, geotechnical risks and hazards

Slope design controls and typical inter-ramp slope angles recommended or achieved in LCT pegmatite open pits are summarised in Table 4. These findings have been collated from feasibility studies and operational experience in seven LCT pegmatite open pits across Australia and Africa.

LCT pegmatite open pits commonly feature a footwall, which parallels the pegmatite, and a hanging wall in country rock, as shown in section in Figure 2a.

The footwall is often controlled by a combination of the dip of the pegmatite body, foliation in the country rock, and major structures. For the hanging wall, structural patterns influencing bench configuration play a significant role in the slope design. Of particular concern regarding hanging walls is the potential for toppling failures where foliation is steeply dipping back into the slope.

Rockfall is also a significant hazard, particularly on steep hanging wall slopes. At some case study sites, rockfall management has become particularly critical, with sand traps and other methods of prevention adopted rather than flattening of the slope.

Table 4 Comparison of global LCT spodumene pegmatites

Wall	Design control	Critical failure mechanisms	Typical inter-ramp slope angles (°)	Comments
Upper weathered zone	Soil or rock mass	Circular Combined rock mass and structure	26–40	Performance is very sensitive to pore pressures
Footwall	Dip of pegmatite body	Planar sliding on pegmatite	20–53	Design is largely controlled by the dip of the pegmatite body
	Major shear zones parallel or transverse to pegmatite	Planar sliding		
	Structures – foliation or bedding	Toppling or planar slide, depending on foliation orientation		
Hanging wall	Major structures	Planar or wedge	46–60	Major structures control inter-ramp scale design
	Structures – foliation or bedding	Toppling or planar slide, depending on foliation orientation		Foliation and all structures are a consideration for bench design
	Structures – all	Rockfall		

7 Conclusion

The growing demand for commodities like lithium, driven by the rapid transition to a green economy, has highlighted the significance of understanding and mitigating geotechnical risks associated with hard rock lithium deposits. This paper has provided a synthesis of the geotechnical controls on slope design for such deposits, focusing on pegmatite (spodumene) orebodies in Australia and Africa.

Geological understanding plays a crucial role in assessing slope stability in hard rock lithium deposits, with the orebody typically presenting an inclined pegmatitic intrusion, creating an open pit setting with footwall and hanging wall formations. The country rocks surrounding the orebody exhibit varying degrees of metamorphism, which can introduce localised geotechnical risks, especially in the presence of weathered material.

Fresh rock mass conditions generally show favourable intact strengths, making structural geology a critical factor in slope design. Key elements of the structure model include the orientation of pegmatite intrusions and potential shearing at the contacts with country rocks, the presence of foliation or bedding, and regional scale faults and shears. Slope stability risks are typically observed at the bench to multi-bench scale.

This paper has presented examples from recent experiences at lithium deposits and operations in Australia and Africa, showcasing the geotechnical ground conditions and slope design challenges. By understanding and addressing these challenges, the mining industry can effectively navigate the complexities of hard rock lithium extraction and enhance safety and efficiency in slope design.

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