Practical Structural Framework for Pegmatite Exploration

Case Study of the Damara Belt, Namibia

TLJ Structural Geology Consulting Ltd

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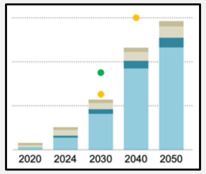
Executive Summary

Pegmatite dykes are strongly folded. This folding is predictable and should guide exploration.

1 Problem

⚠ Structural frameworks for pegmatite deposits are not well developed.

⚠ Contributes to difficulty exploring beneath cover, unfocussed exploration strategies, lower drilling success rates & erroneous or unrealistic 3D models & resource estimates.



Lithium demand growth

2 Case Study (Namibia)

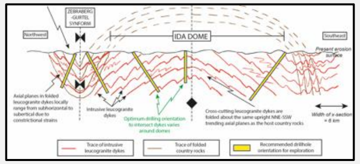
Damara Belt Case Study, Namibia

- Damaran pegmatites are mined for uranium, tin & tantalum and have strong lithium potential.
- Damara Belt is a well studied analogue for understanding collisional pegmatite systems globally.

3 New Insights

Folding controls orientation & geometry of leucogranite & pegmatite dykes.

High-temp metamorphism prevented the development of localised faults & shear zones.



4 Exploration Applications

🔥 **Regional-Scale Strategy** – Avoid hunting for narrow faults & shear zones (not well developed in this environment); focus instead on dome limbs and km-scale interference fold architecture.

🔥 **Camp-Scale Strategy** – Use predictable geometries of folded leucogranite/pegmatite dykes to plan drillhole orientation: maximise hit rates & reduce missed targets.

🔥 **Deposit Scale Strategy** – Constrain 3D geological models to fold geometry for robust mineral resource estimates and more efficient expansion of known resources.

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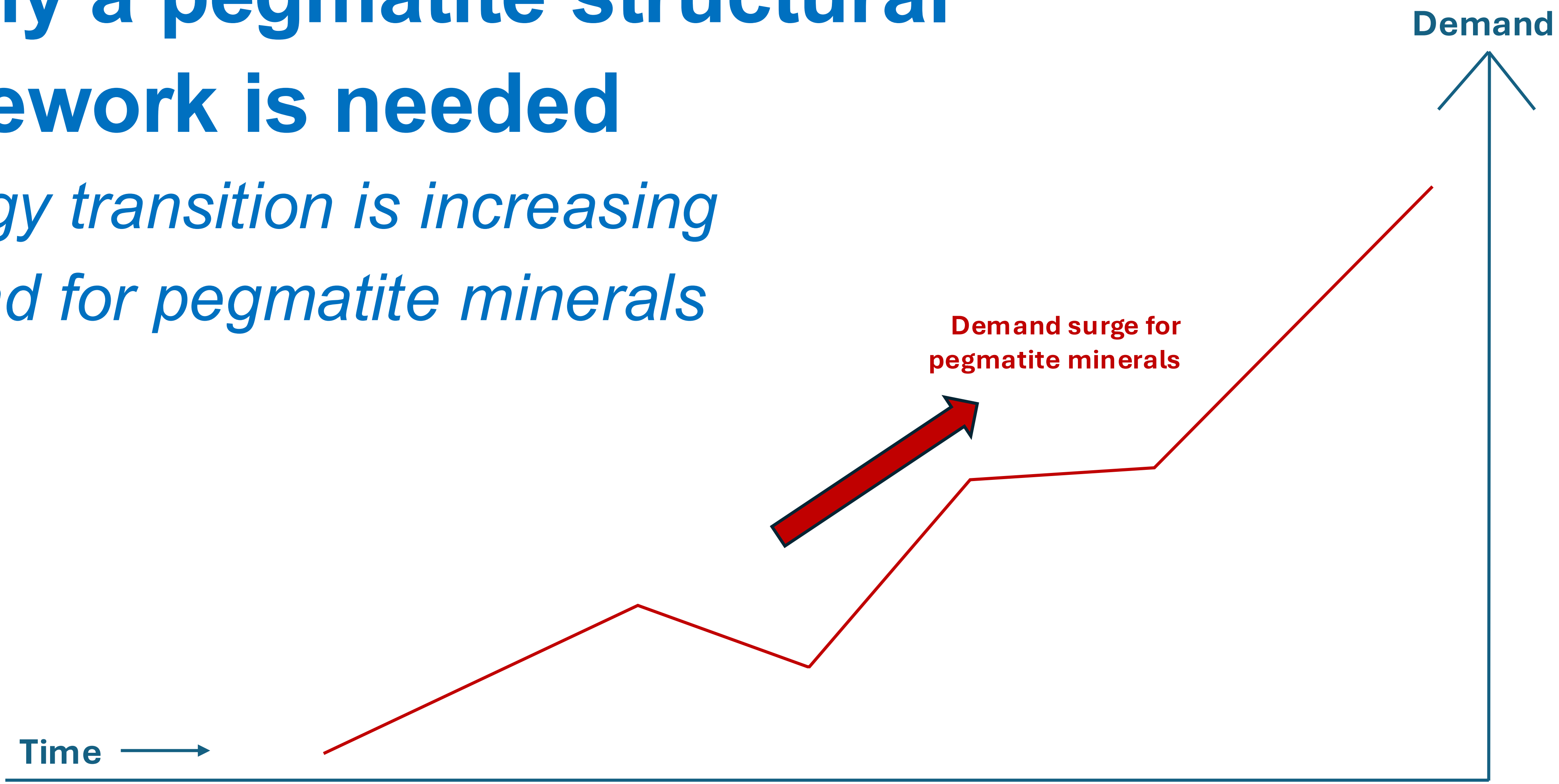
1. Why a pegmatite structural framework is needed

- Energy transition is increasing demand for pegmatite minerals



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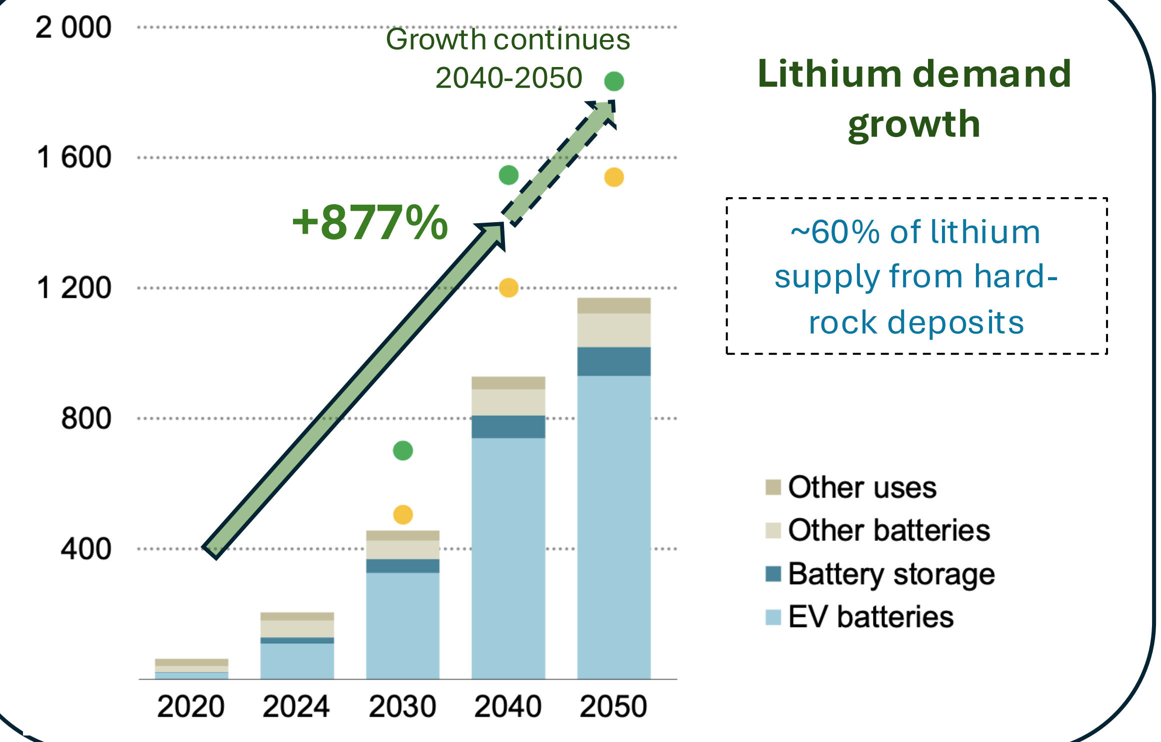
Lithium is leading a **long-term demand boom** for pegmatite minerals

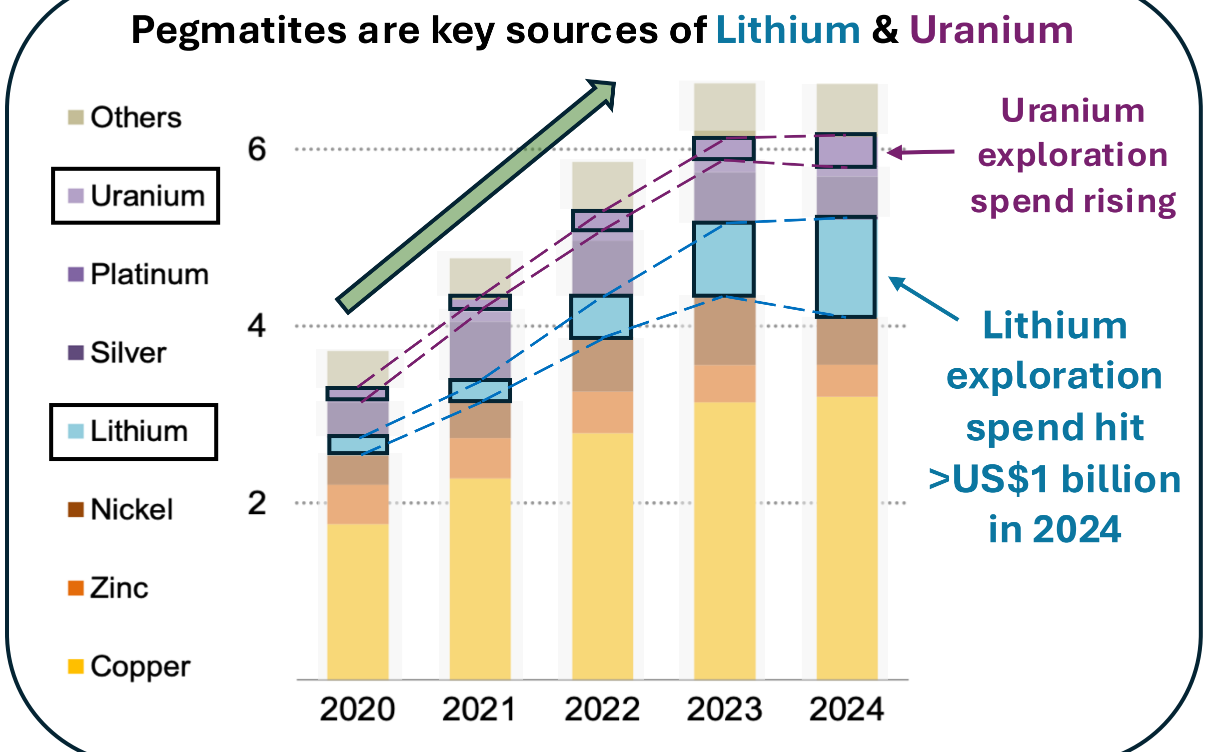
Lithium exploration spend exceeded **US$1 billion** for the first time in 2024

Global lithium demand growth 2020-2050, kt



Source: IEA analysis based on S&P global

Critical mineral exploration spend, US$B



Source: IEA analysis based on S&P global

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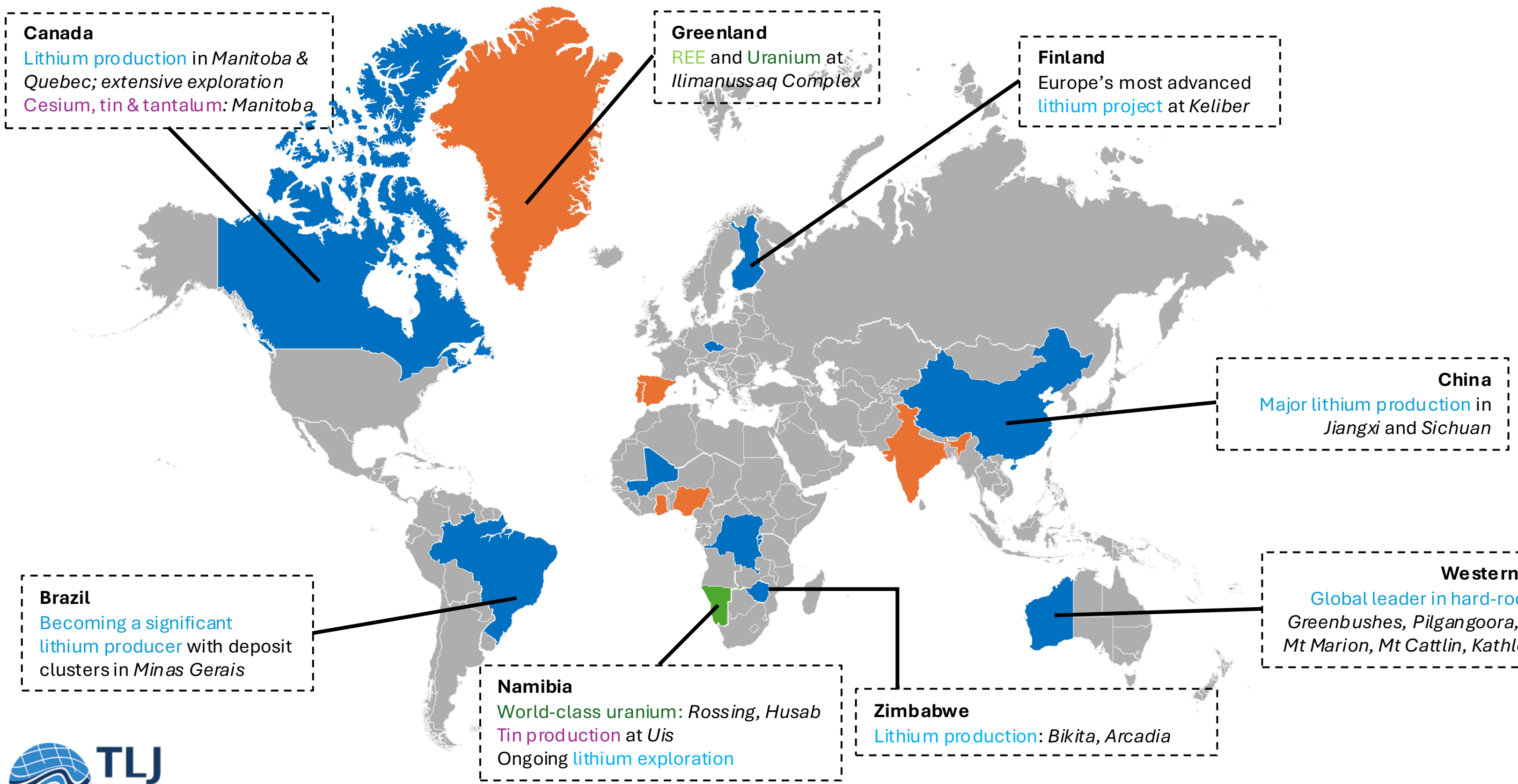
Pegmatite **mining & exploration is expanding globally**

All pegmatite deposits have a structural control (often overlooked and not recognised)

Selected pegmatite mining & exploration districts in 2025 (non-exhaustive list)



Commodity	Demand Drivers	Global Outlook
Lithium	Energy Transition (*EV batteries, Energy Storage Systems*)	**Booming** (+122% from 2024-2030)[1]
Uranium	Energy Security & Decarbonisation	**Likely rising** (+50% nuclear capacity rise by 2050 possible)[1]
Tin	Solder use in growing electronics industry	**Rising** (+14% from 2025-2030)[2]
Magnet Rare Earth Elements (REE)	Electric Vehicle Motors, Supply Chain Security concerns	**Booming** (+42% from 2024-2030)[1]

Map Key	
Blue	Mine or advanced development stage
Orange	Early development stage or exploration
Green	Namibia = location of present study

Sources: [1] IEA Global Critical Minerals Outlook 2025; [2] Mordor Intelligence

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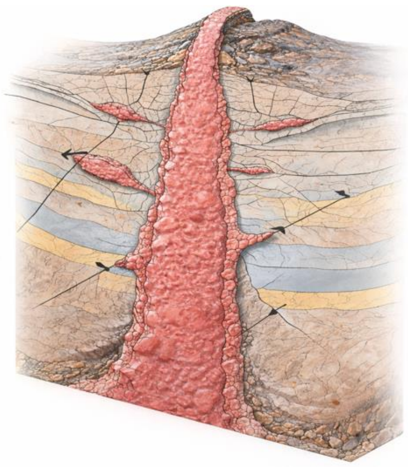
Pegmatite intrusion is a **structurally & tectonically controlled process**

Structure controls the geometry while tectonics provides the driving force

Structural-tectonic controls on pegmatite dykes *(and by extension pegmatite deposits)*

Dyke intrusion is a structurally-controlled process



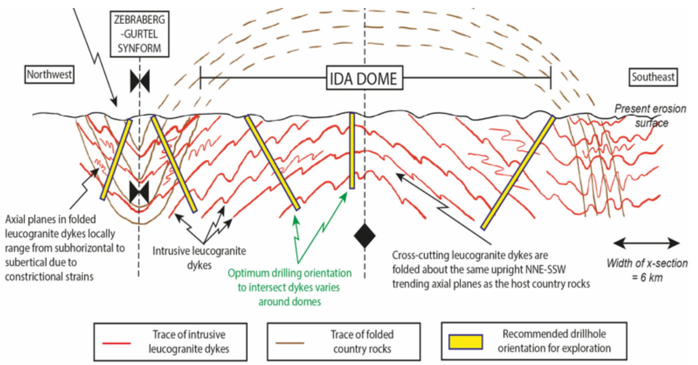
Hydrofracturing

Ductile deformation

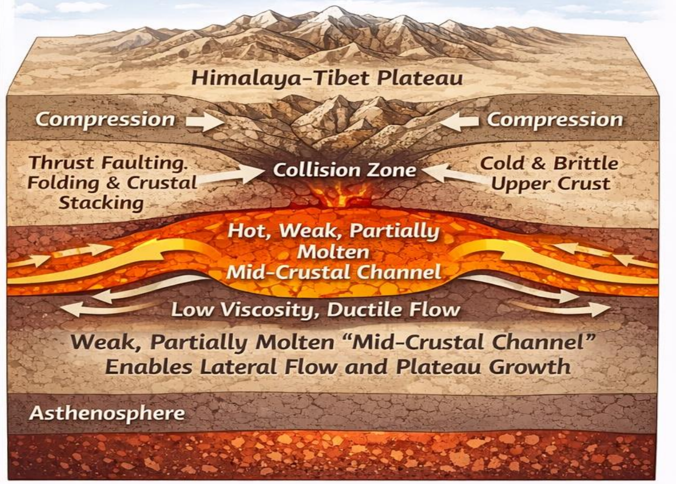
Pervasive magma injection

Deformation can alter dyke geometry after emplacement

Folded dykes in the Damara Orogen (this study)



Tectonic events drive pegmatite magmatism



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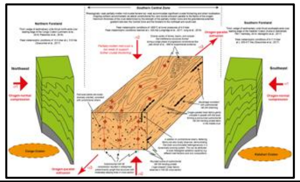
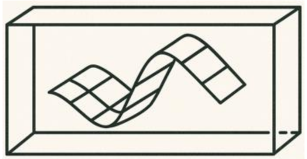
Common exploration problems need structural geology support

This improves drilling success rates, prioritises targets, & constrains 3D models

Common Problems	Common Causes	Structural Geology Solutions
Difficulty **exploring beneath cover**	Limited data available to guide exploration decisions	Use structural relationships to predict dyke orientations where exposure is limited, maximising value of sparse outcrop, core & geophysical datasets 
Misaligned or unfocused **exploration strategies**	Models designed for lower metamorphic grades or other deposit types (e.g. orogenic gold) don't translate well to high-temperature pegmatite terrains	Use deposit-to-regional structural frameworks designed specifically for high-grade metamorphic terrains 
Low success or missed **drill targets**	Not recognising or understanding structural controls and post-emplacement modifications to orebody geometry	Understand structural controls on dyke geometry and use this to orientate drillholes and maximise drilling efficiency. 
Poorly constrained **3D geological models**	Structural constraints (e.g. due to folding) are often not sufficiently understood or implemented into workflows	Constrain 3D models to measured fold axes, lineations, and dome geometries for more realistic geological modelling 

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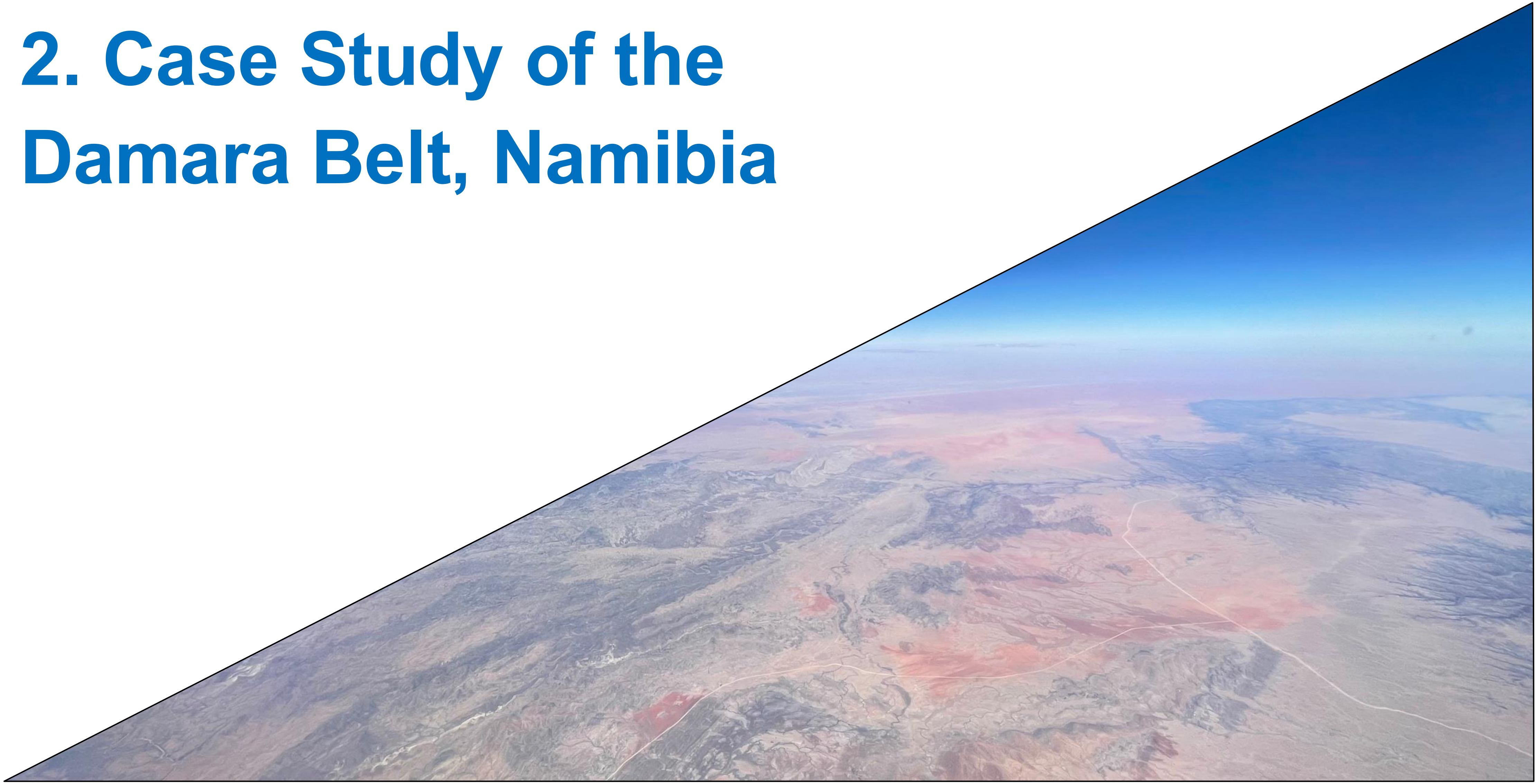
2. Case Study of the Damara Belt, Namibia



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World-class U mines, Sn & Ta production, & Li exploration

Namibia’s Damara Belt is a premier case study for global pegmatite mineral systems

Flagship pegmatite mines in Namibia’s Damara Belt

Rössing

One of the world’s longest-running and largest open-pit uranium mines - production began in 1976 with mine life extended to 2036[1]

Husab

Discovered in 2006, production began 2016. In 2024, Husab was the world’s 3rd largest uranium mine with 7% of global production[2]

Uis

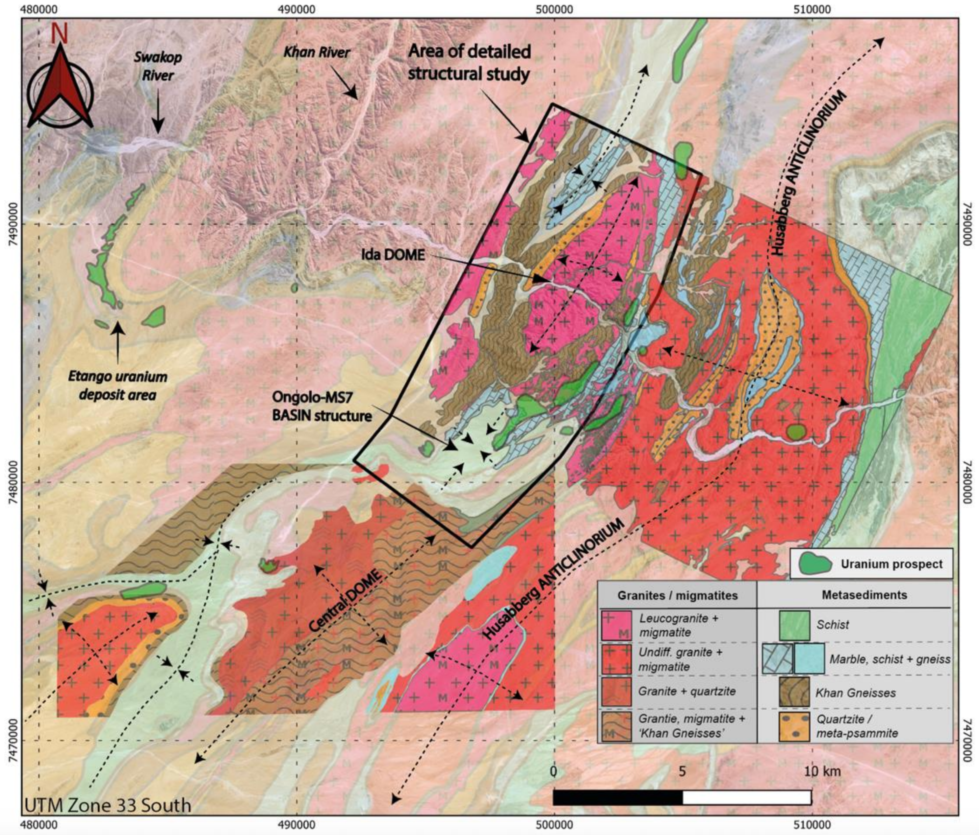
Tin discovered in 1911 and mined continually from 1958-1990. Restarted in 2017 with tantalum by-product & lithium potential[3]

Sources: [1] CNNC Rossing Uranium. [2] World Nuclear Association; Namibia Chamber of Mines. [3] Andrada Mining.

Systematic structural mapping undertaken across a 400km^2 area

Results guide future exploration in the highly prospective Damara Belt

New geological map of the study area



Key Methodology

Methods	*Description*
Structural dataset	Systematic collection of >1,600 outcrop-scale data points - fold axes, foliations, lineations, dyke contacts
Kinematic observations	S-C and asymmetric fabrics documented to determine shear sense on dome limbs
Melt-strain relationships	Petrographic relationships used to determine the relative timing of magmatism & deformation
Regional strain analysis	Steronet analysis used to visualise fold axis orientations, lineations & relationship to granites
Conceptual modelling	Integration of field data to produce a conceptual 3D model linking dyke orientations to structural fabrics
Regional tectonic model	Structural data integrated with metamorphic & age data to critically evaluate regional tectonic models

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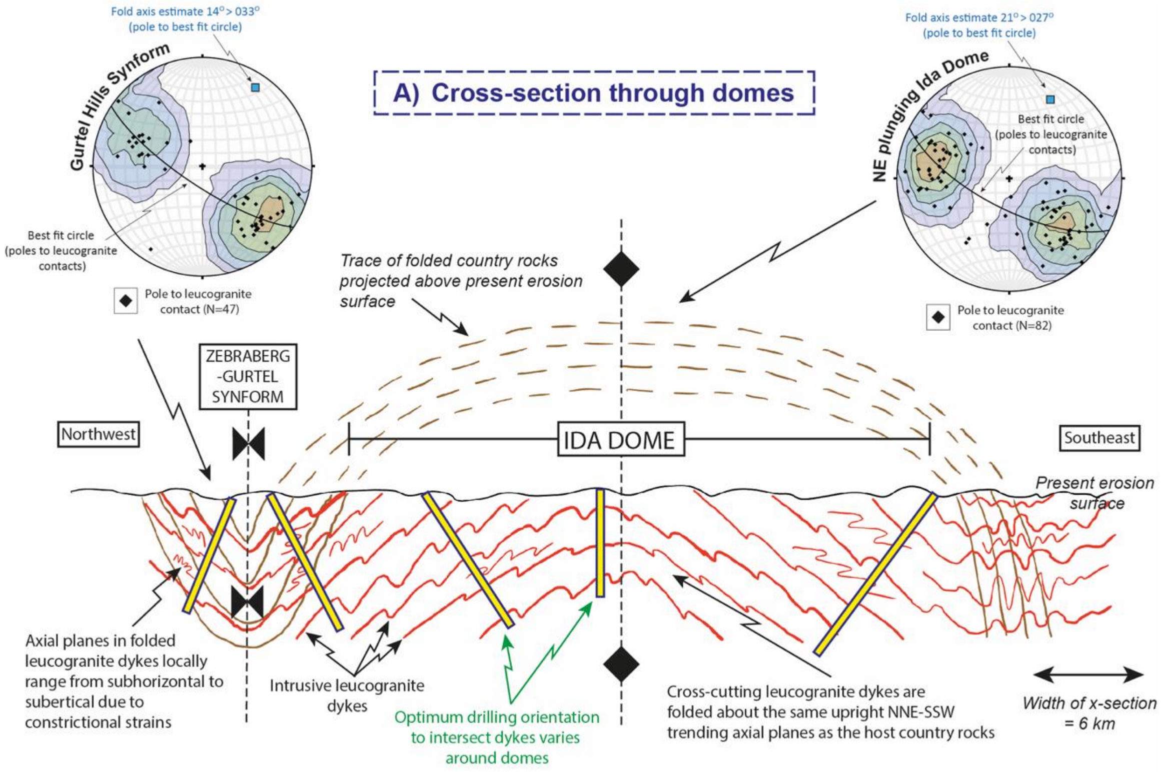
3. Results: Folding controls dyke orientation

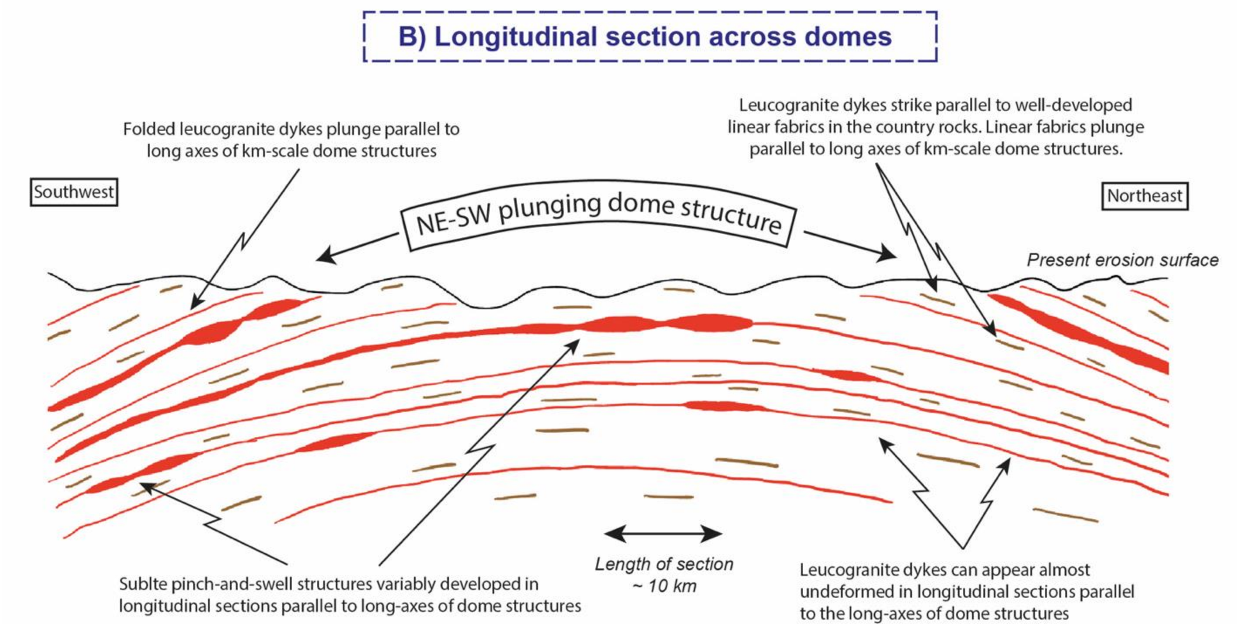
Dykes form **systematic & predicable** patterns around km-scale domes

Dykes consistently dip similarly to fold limbs and plunge parallel to fold axes

Dykes folded in cross-section



Dykes plunge parallel to fold axes (long section)



Trace of intrusive leucogranite dykes

Trace of folded country rocks

Recommended drillhole orientation for exploration

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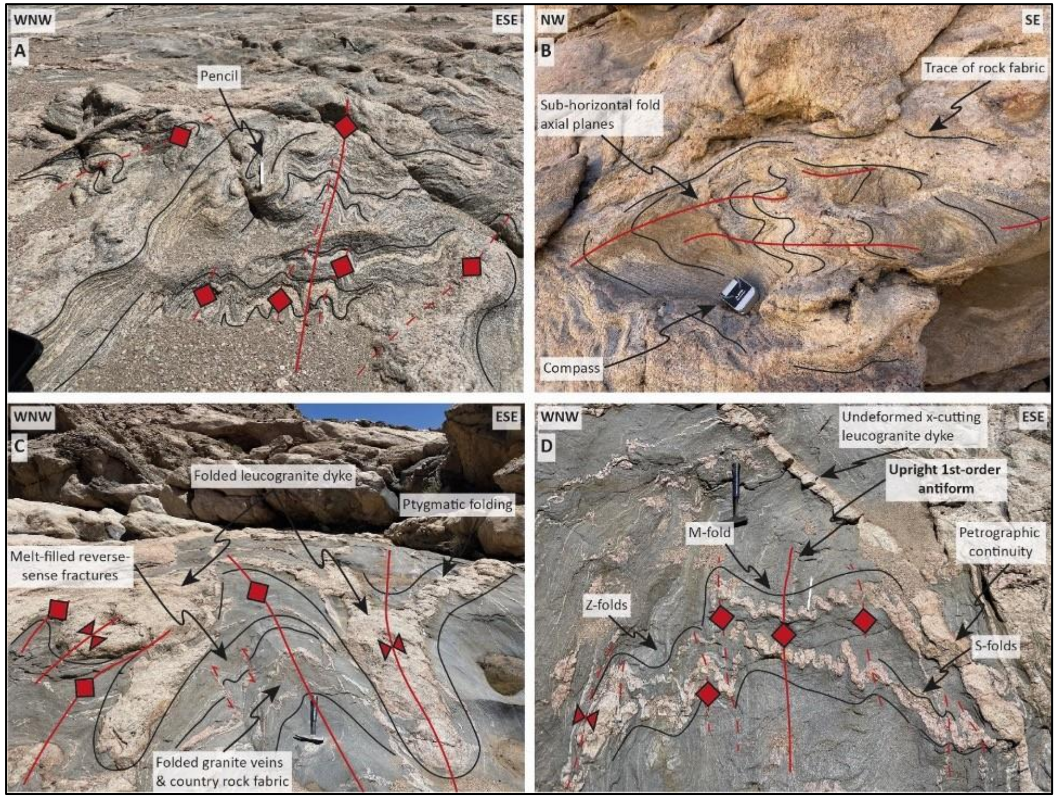
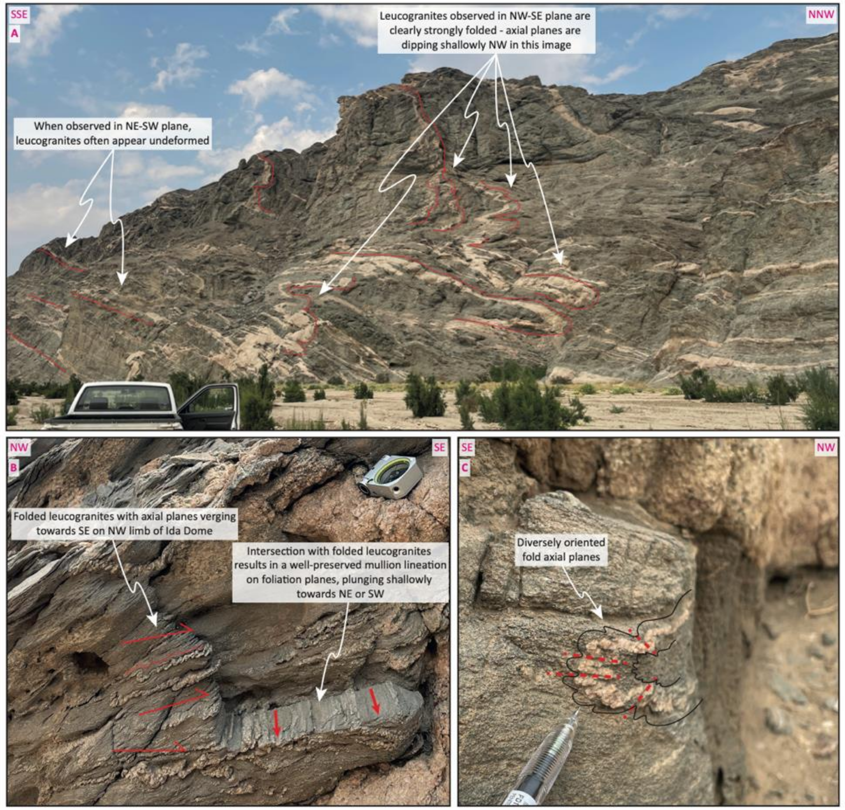
Dykes are universally **strongly folded** at all scales

This is true amongst migmatites in dome cores & in metasediments on dome limbs

Folded leucogranite amongst migmatites



Folded leucogranite in metasediments



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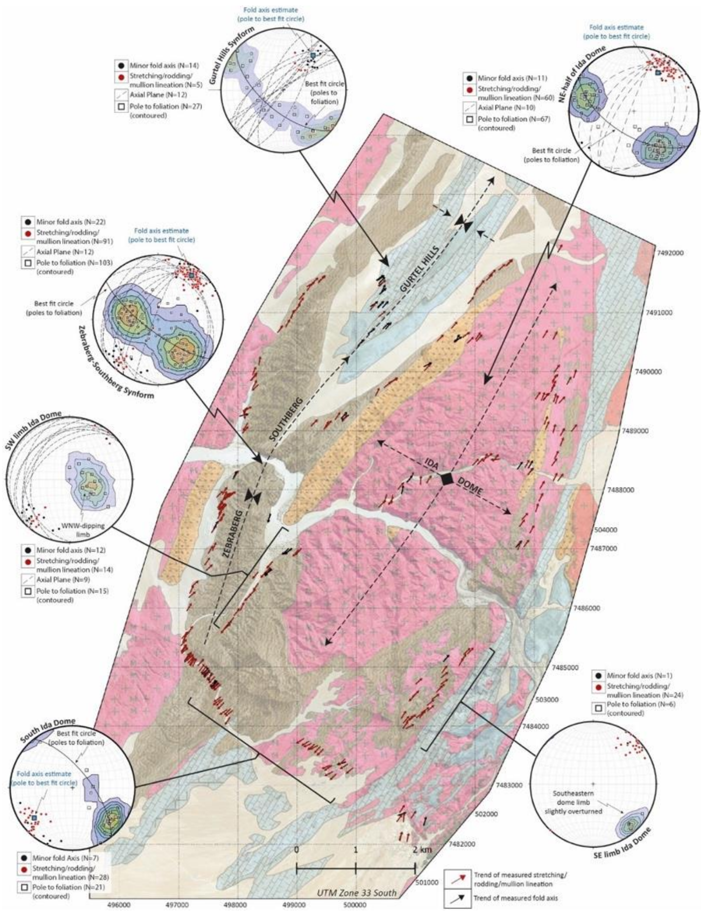
Dykes are consistently **folded into parallelism with dome axes**

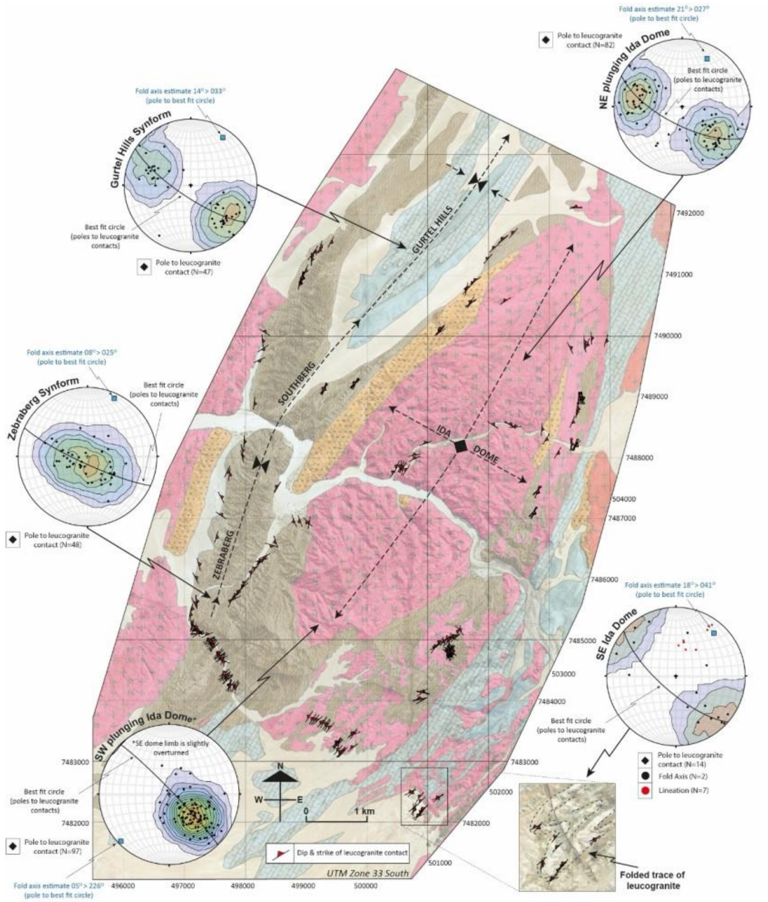
Fold patterns in the leucogranite dykes closely match fold patterns in country rocks

Country rock data - Ida Dome



Fold axes statistically defined on stereonets plunge shallowly NE-SW in both country rocks and in intrusive leucogranite dykes

Leucogranite dyke data - Ida Dome



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4. Applying these results to mineral exploration

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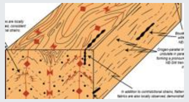
Fieldwork data reveals that **structural features are inter-related**

Fold axis & lineation data can reliably **predict the orientation of folded dykes**

Dataset / Feature		Relationship to other structures	Exploration / modelling use	Importance
	**Lineations (L-tectonites, rodding, mullions)**	Consistently parallel to fold axes and dyke strike	Key predictor of dyke trend	**Very high**
	**Fold axes**	Dykes folded around these same fold axes	Controls dyke orientation & key predictor of dyke trend	**Very high**
	**Dyke orientation**	Controlled by folding: strike parallel to fold axes and dip approximately mimics dome limbs at km-scales	Determines drillhole orientation and grade continuity	**Very high**
	**Foliation (S-tectonite planes)**	Defines limbs of domes & basins; dykes dip approximately parallel to dome limbs at the km-scale	Guides dip & orientation of target dykes when working at km-scales in 3D models; correlation progressively becomes less robust at smaller scales	**High**
	**Axial planes**	Typically upright at km-scales; locally variable dip at individual outcrops due to constrictional strains	Take care - constrictional strains cause diverse orientations of axial planes at deposit scales	**Moderate**
	**Regional structural grain**	Dykes, fold axes and lineations dominantly strike NE-SW throughout the southern Central Zone	Take care – heterogeneities locally rotate structures into different orientations e.g. at the MS7 prospect	**Moderate**
	**Boudin necks**	Parallel to lineations, fold axes & dyke strike	Fluids *may* pool in boudin necks (more research needed)	*Unclear*
	**Shear-sense indicators**	Opposite shear senses on opposite dome limbs confirms coaxial strain / pure shear regime	Important for 3D symmetry of structures at km-scales, limited direct applications in exploration or modelling	**Low**

Lineations, fold axes & limb geometry **guide exploration drilling**

Dyke orientation is predictable around dome structures even with limited outcrop

Using structural geology to reduce missed drilling targets

Dykes are folded into parallelism with regional fold axes

Structural data makes these fold patterns predictable

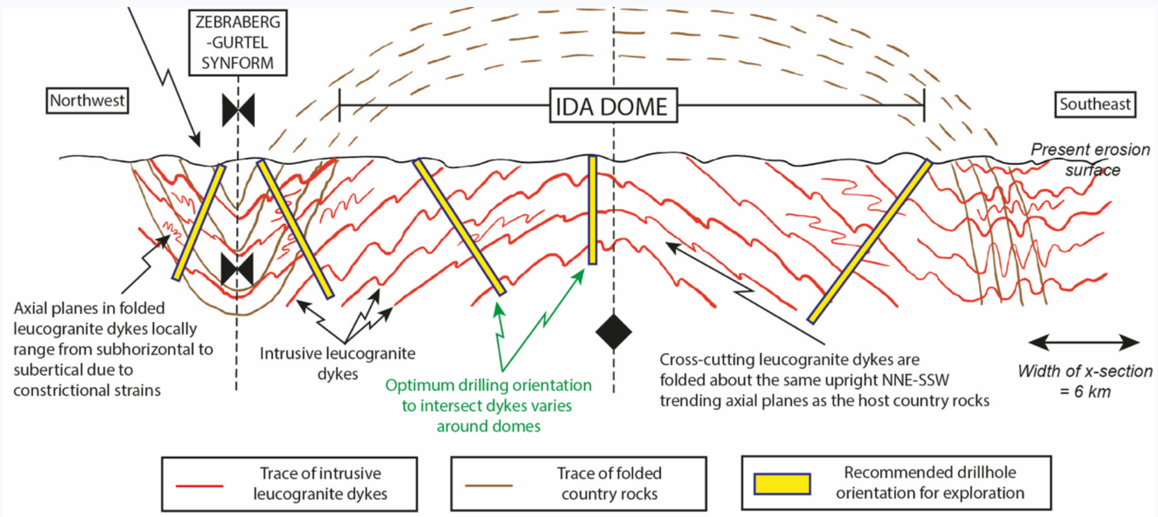
- Lineation data
- Fold axes
- Dome limbs

✅ **Allows drillholes to be suitably orientated to intersect folded dykes**

Outcomes include:

✅ *Intersect dykes at optimum angles*
✅ *Fewer missed targets since structural geometry is well understood*
✅ *More accurate assessment of orebody thickness, grade & geometry*
✅ *Easier to expand known resources by understanding 3D dyke geometry*

Schematic cross-section showing optimum orientation of drillholes to intersect folded dykes around km-scale dome structures



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3D geological models should use structure as a primary constraint

Structural understanding increases robustness of models & resource estimates

De-risking future project development & supporting investor confidence

Dykes are folded into parallelism with regional fold axes

Structural data makes these fold patterns predictable

- Lineation data
- Fold axes
- Dome limbs

✅ **Incorporating local structural trends, fold geometries, and orebody plunges vastly improves implicit models**

Outcomes include:

✅ *Much more realistic geological interpolation between drillholes*
✅ *Potentially revealing new 'hidden' structural controls via 3D visualisation*
✅ *More accurate & robust mineral resource estimates*
✅ *De-risking project development in the future*

Modern 3D modelling software incorporates structural data as primary inputs for rapid implicit modelling workflows

- Apply structural trends, fold frames & anisotropy fields
- Rapid model iteration as new structural datasets added (surface mapping, downhole data, etc.)

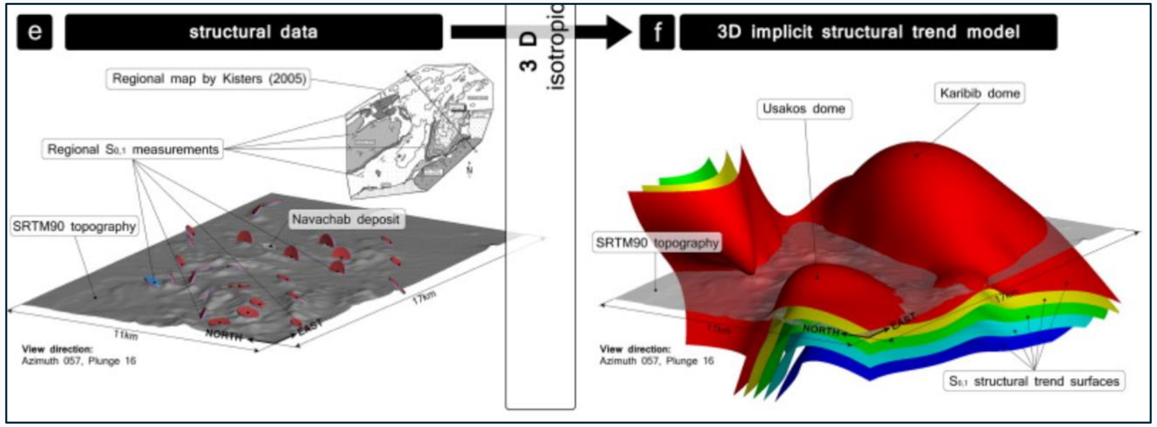

Image source: Vollgger et al., 2015 – Implicit modelling to assess structural trends at the Navachab Gold Deposit, Namibia

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Example workflow to incorporate structural data

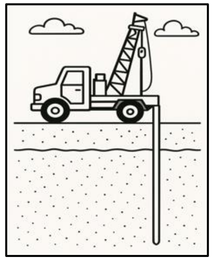
This is especially useful when exploring beneath cover (with limited rock outcrop)

Example workflow:

1) Map lineations & fold axes first – they help define dyke strike

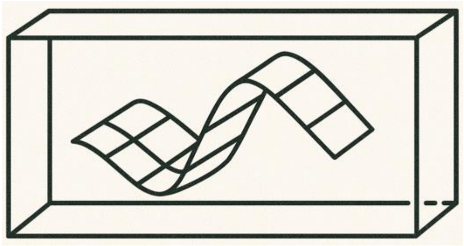
2) Use foliation planes and stereonets to define dip angle of fold limbs

3) Relate dyke dips to dome geometry – dykes broadly dip parallel to limbs and strike parallel to axes

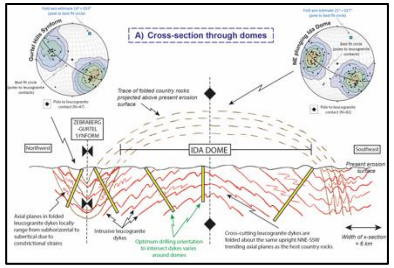


4) Drill orthogonal to dyke planes to maximise intersection & grade accuracy

5) Collect live structural data from core or optical televiewer to continually update understanding



6) Build 3D framework – constrain dyke wireframes to fold-controlled orientations



7) Test, validate and iterate the model – treat as an evolving hypothesis

8) Continually integrate updates & refinements into model & workflow as new data collected

Structural Geology makes dyke orientation predictable

✅ **Drillholes orientated more accurately**

> Higher success rates, fewer missed targets.

✅ **Realistic structure-constrained 3D geological models**

> More robust mineral resource estimates.

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5. Exploration strategy tailored to regional tectonic setting

At the regional scale: A case of Lateral Constrictional Flow

The entire mid-crust flowed *en-masse* during the orogeny, producing complex folds

i. Metamorphic temperatures exceeded 800^{O}C in Central Zone

ii. This triggered widespread partial melting & granite magmatism

iii. This reduced viscosity of the crust on a regional scale

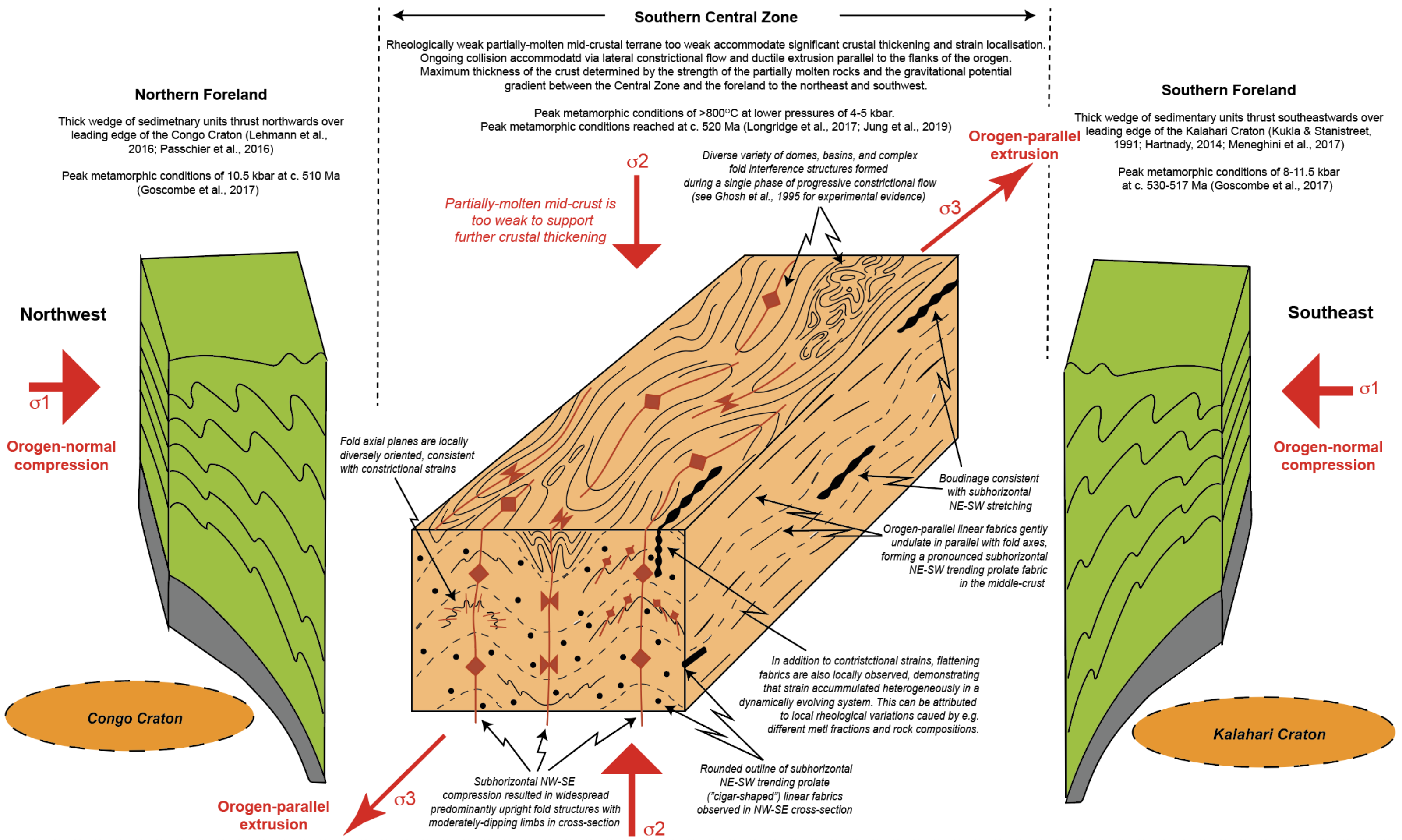
iv. This prevented strain from localising into narrow / distinct shear zones

v. The mid-crust instead deformed en-masse at a regional scale for millions of years (perhaps 10s Myrs)

vi. The mid-crust behaved like a slow, high-viscosity fluid

vii. This formed complex fold patterns over the course of millions of years

Lateral Constrictional Flow in the mid-crust of the Damara Orogen



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Alternative tectonic models are inconsistent with the data

Tectonic models are important for developing holistic mineral systems understanding

	Lateral constrictional flow	Polyphase Deformation	Diapirism	Tip-line folds above blind thrusts	Core complex / extensional collapse
For ✅	✅ *Widespread constrictional fabrics* ✅ *Pervasive strain distribution without localisation into narrow shear zones* ✅ *Isobaric heating path explained by NE-SW stretching offsetting NW-SE shortening* ✅ *Favourable metamorphic conditions – high T with widespread melt present*	✅ Ramsay Type-1, 2 and 3 fold interference patterns observed	✅ Leucogranite magmatism in dome cores	✅ Folding consistent with NW-SE compression	✅ Migmatite-cored domes superficially resemble core complexes formed by extensional collapse
Against ❌	✅ *Compatible with all available data*	❌ Different sequence of deformation events at each dome; cannot be explained in context of regional tectonic events	❌ Lineations plunge parallel to fold axes rather than radially outwards, suggesting plate tectonic forces dominated over diapiric forces.	❌ Regional strain pattern is coaxial – no evidence for foreland-vergent thrusting ❌ Orogen-parallel lineations are not consistent with foreland-vergent transport ❌ Thrust faults not observed ❌ Granulite-facies temperatures & widespread partial melting restrict strain localisation into distinct thrusts	❌ Isobaric heating path to peak metamorphic conditions rules out crustal thinning associated with extensional tectonics ❌ No field evidence observed in this study for an extensional detachment shear zone

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Tectonic models guide **exploration strategy & focus resources**

They avoid ineffective resource allocation & ensure local deposit models are realistic

Structural controls vary significantly by metamorphic grade & tectonic setting

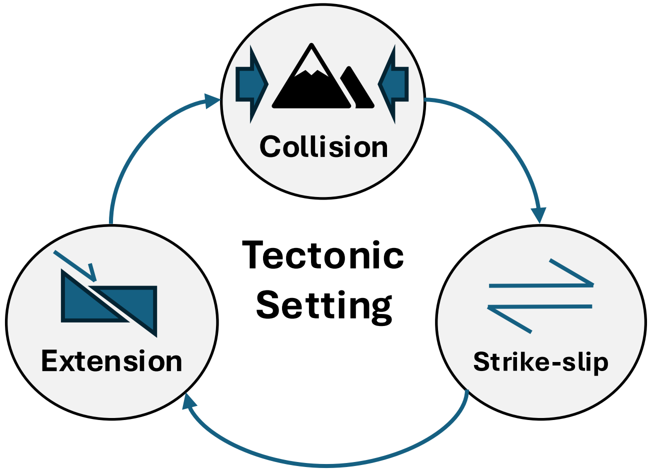
Cold — **Metamorphic environment** — **Hot**

Brittle deformation

Strong strain localization
Faults & shear zones dominate
Create permeability & focus fluids

Exploration targets:

- Major faults / shear zones
- Jogs, bends, splays
- Fault intersections
- Damage zones



Ductile deformation

Little strain localization
Faults & shear zones not well developed
Entire crust deforms as a viscous solid

Structural features:

- Domes, basins & interference folds
- Strong melt-strain relationships
- Highly complex progressive deformation spread over huge areas which persists for millions of years

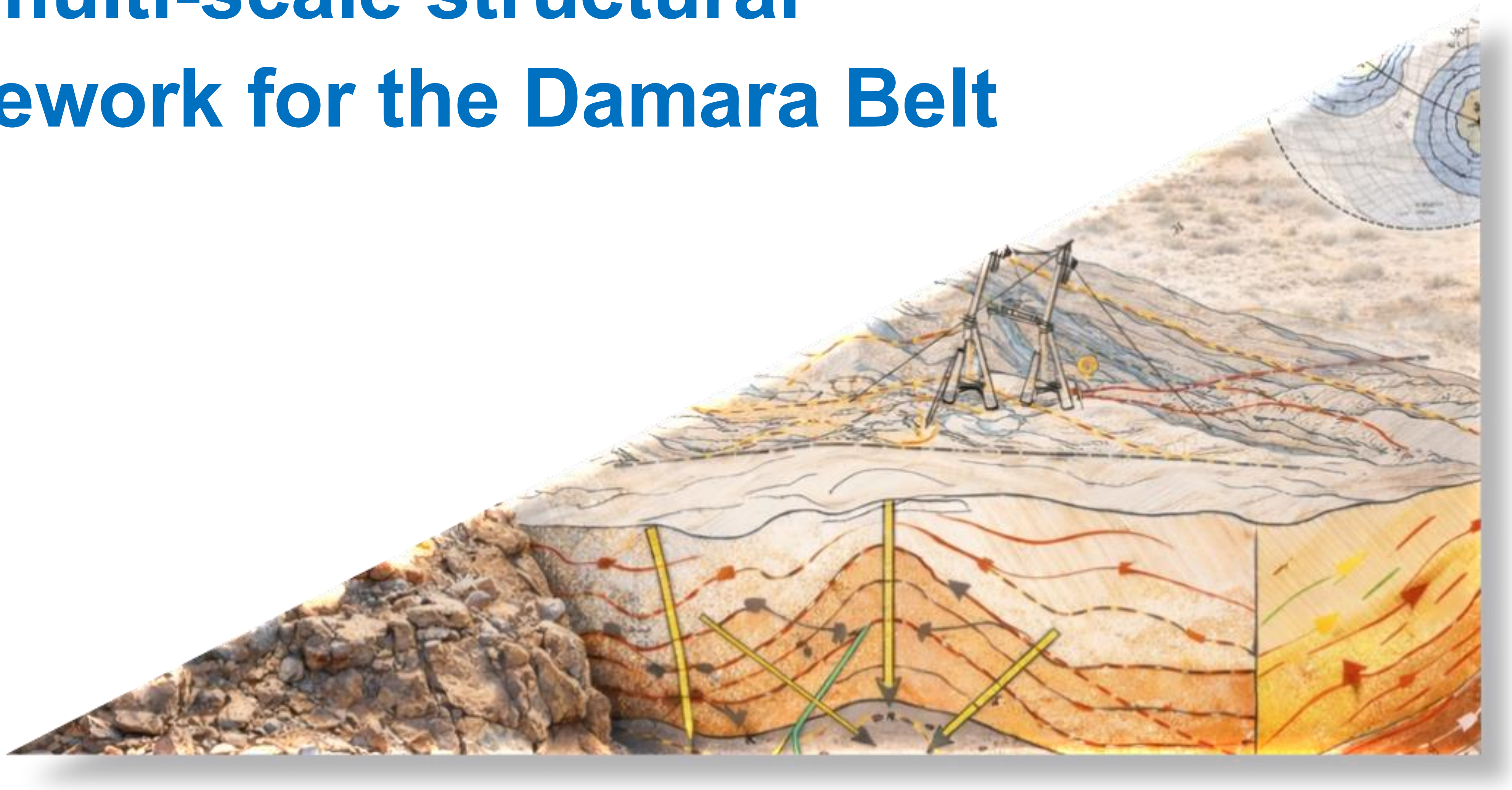
Well-developed — Maturity of exploration frameworks — **Still developing** ?

Key Takeaway

✅ **Tectonic setting tells us what type of structural controls to expect in a specific environment**

> Target features with the most realistic chance of success & avoid chasing unrealistic models.

6. A multi-scale structural framework for the Damara Belt



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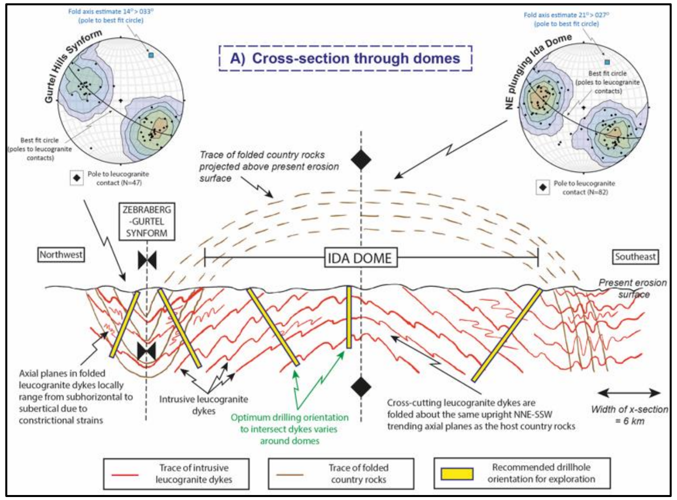
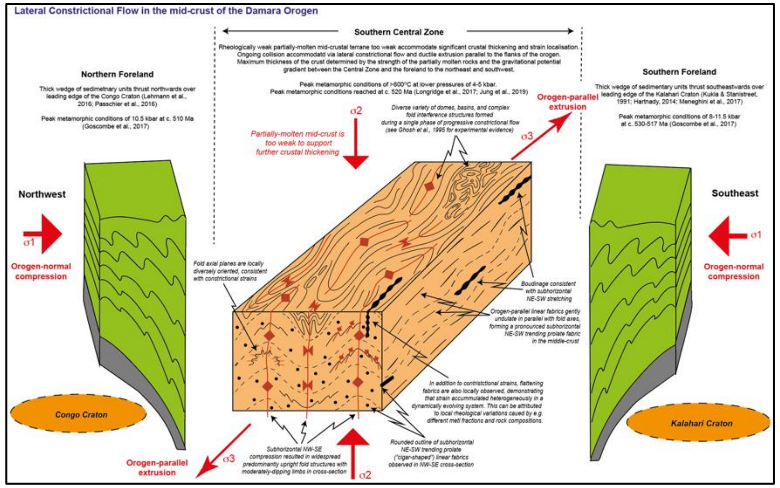
A consistent **deposit-to-regional** structural framework is defined

Syn-tectonic dykes were folded into consistent patterns during the Damara Orogeny

Narrow faults & shear zones did not develop since high-T metamorphism restricted strain localistion*





Deposit Scale

Folded leucogranite dykes

Camp Scale

Dykes folded into parallelism with dome-and-basin structures

Regional Scale

Lateral constrictional flow under high-temperature metamorphism* drove complex fold interference

*Granulite-facies metamorphic conditions with regional temperature >800^{O}C existed for millions of years (Longridge et al., 2017; Jung et al., 2019)

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This **guides exploration** across scales & project execution stages

Improving drilling success rates, resource models & target selection

Recommendations for mineral exploration in the Damara Orogen:

Exploration Targeting (regional-scale)
Distributed deformation characterised by complex interference fold architecture

Things to focus on:

- ✓ Steeply-dipping limbs between domes may favour buoyancy-driven metamorphic/magmatic fluid flow
- ✓ Strongly foliated lithologies (schists) may favour deformation-driven metamorphic/magmatic fluid flow
- ✓ Lithological boundaries (carbonates) may create redox boundaries promoting uranium deposition[1]

Things to avoid:

- ❌ Very little localised deformation (due to the high-T conditions) – faults/shear zones not well developed
- ❌ Leucogranites are regionally pervasive – magmatism was not localised into narrow structures or domains

Outcomes:

- *Avoid unrealistic fault and shear-zone driven exploration hypotheses*
- *Focus sparse resources into realistic ideas which deliver max impact*

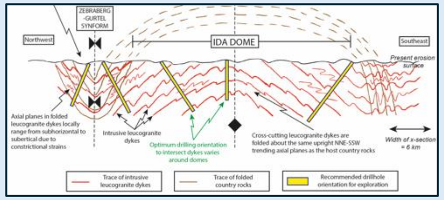
Drillhole Planning (camp-scale)
Dykes folded into parallelism with km-scale fold axes

Things to focus on:

- ✓ Map key structural features (lineations, fold axes, foliations, dyke contacts, axial planes)
- ✓ Use conceptual understanding (Chapter 4) to predict subsurface dyke geometry

Outcomes:

- *Accurate planning of drillhole orientation ensures mineralised dykes are intersected at optimum angles*
- *Fewer missed targets results in significant cost savings and greater capital efficency*



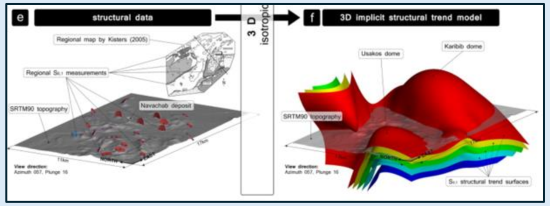
Modelling & Expansion (deposit-scale)
Complex local fold patterns understood via detailed structural data collection

Things to focus on:

- ✓ Collect structural datasets (lineations, fold axes, foliations, etc.) from surface mapping & drill data
- ✓ Apply structural datasets to 3D modelling – use structure as a primary constraint on model geometry

Outcomes:

- *Realistic 3D geological models producing robust & reliable mineral resource estimates*
- *Structural understanding of orebody geometry & plunge allowing more efficient resource expansion*



Sources: [1] Kinnaird & Nex, 2007.

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This model is underpinned by **multiple years of field-based research**

Documented in a 63-page primary research report

Link to full open-access report on ResearchGate

👉 https://www.researchgate.net/publication/397546281_Structural_framework_for_uranium-bearing_pegmatite_dykes_in_the_Damara_Orogen_Namibia


Thomas Lloyd Jones – Technical Research Report 11th November 2025

11th November 2025

Structural framework for uranium-bearing pegmatite dykes in the Damara Orogen, Namibia

Thomas Lloyd Jones

This work formed part of T. Jones' PhD research at the University of the Witwatersrand. It was not submitted for examination and is instead made publicly available for industry and academic use.

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Jones, T.L. 2025. Structural framework for uranium-bearing pegmatite dykes in the Damara Orogen, Namibia. *Technical PhD research report, University of the Witwatersrand, South Africa.*

Research Sponsors:

Deep Yellow LIMITED

cimera DSTI-NRF Centre of Excellence for Integrated Mineral and Energy Resource Analysis

This framework will **continue to develop** as the volume of data grows

It can be applied immediately & expanded to other pegmatite deposits globally

	Action Points	How to accomplish
1. Application	i) Apply to **Drill Targeting** & **Orientation Planning**	Use framework in Chapter 4 & 6
	ii) Apply to **3D Geological** & **Resource Modelling**	Use framework in Chapter 4 & 6
	iii) Provides **Structural Context** for Mapping & Core Logging	Use framework in Chapter 4 & 6
	iv) Provides **Tectonic Context for Exploration Strategy**	Use framework in Chapter 5 & 6
2. Validation	i) **Validate** the model against real-world results	Compare predictions to live subsurface drill, televiewer, and 3D model data – quantify misfits
	ii) Continually **refine & evolve** the model	Treat as a living hypothesis – integrate new datasets back into the model; iterate and evolve
3. Expansion	i) Apply methodology to **lithium-cesium-tantalum (LCT)** and **tin-bearing** pegmatites in the Damara Orogen	***Replicate the workflow***: i. Rapid structural reconnaissance – geophysical & satellite data, field proofing ii. First-pass model: test, validate, iterate & evolve iii. Integrate commodity & region-specific datasets
	ii) Apply methodology to **orogenic pegmatites globally** – a global structural framework for pegmatite exploration	

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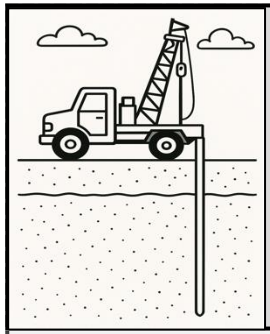
Structural understanding **preserves & unlocks value** in complex terrains

Costs are offset by small improvements in drilling efficiency; bigger upsides possible

Example cost of drilling programme

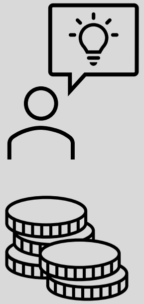


Cost of 7,000m drilling campaign*

RC drilling = **US$ 700,000**

or

Diamond drilling = **US$ 1 million**



Specialist structural geology input

~US$ 30-40k

equivalent to:

5% *of RC drilling budget*

or

4% *of diamond drilling budget*

Value added through structural geology

If drilling efficiency improves by 4-5%
✅ **Already cost effective**

Ensuring good targets not abandoned from misoriented drilling
✅ **Preserves option value on targets potentially worth US$M**

Incorporating structural understanding into target prioritisation
✅ **Contributes meaningfully to new discoveries**

- ✅ Reusing **good structural frameworks compounds** across multiple campaigns to 6-figure USD savings even on modest projects
- ✅ Structural framework & data provides basis for **improved geological & resource modelling** – impacting project valuation & financing
- ✅ **Stronger technical credibility** with investors & JV partners
- ✅ **Maximises value of existing datasets** e.g. geophysics
- ✅ **Faster decision-making speed** if a structural framework is already in place

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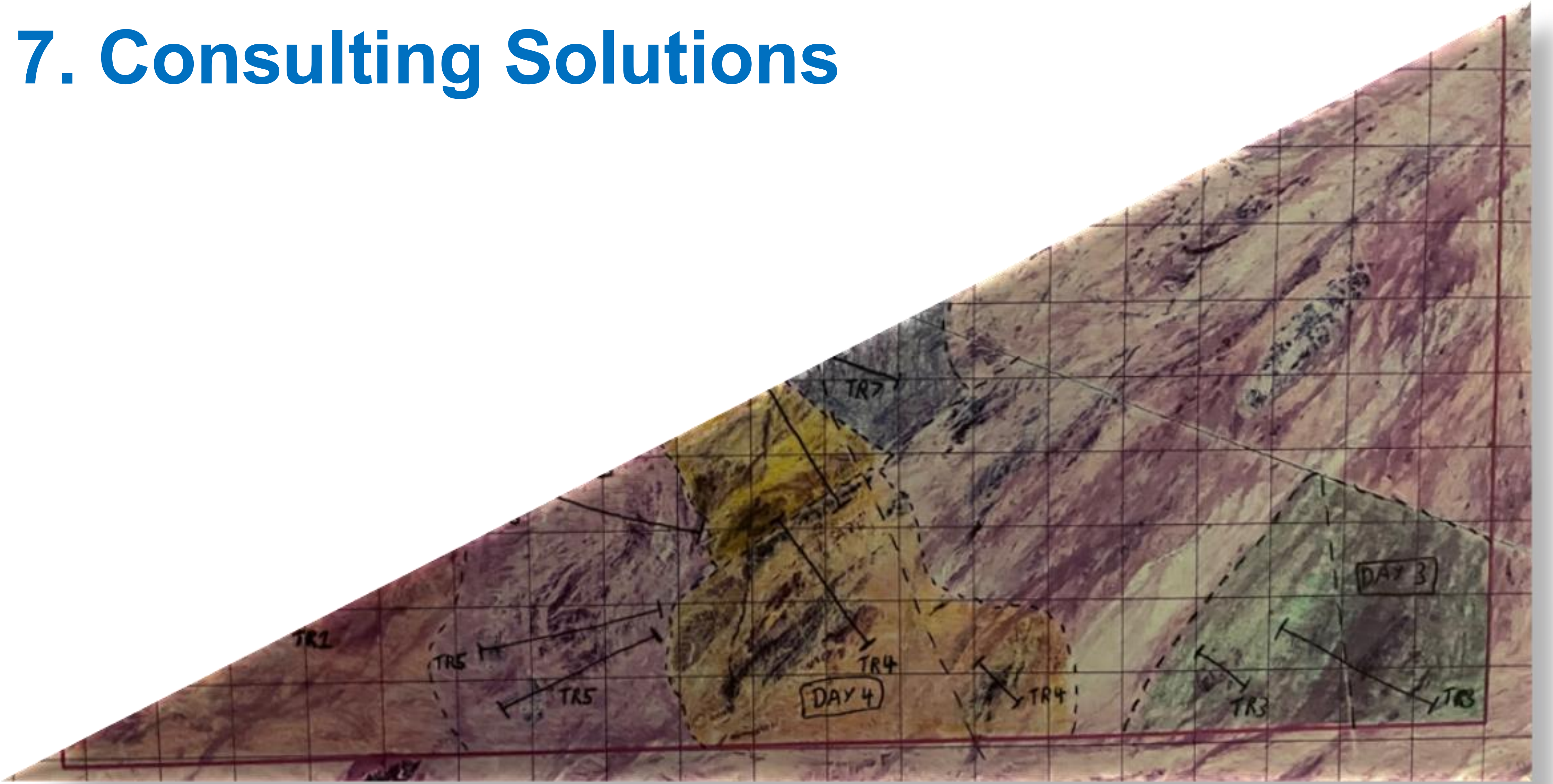
**Cost assumptions used: Diamond drilling = US$ 150/m, RC drilling = US$ 100/m. Actual costs vary significantly based on logistics & accessibility, jurisdiction, drill programme complexity, etc.*

7. Consulting Solutions



TLJ Structural Geology Consulting Ltd

Supporting **complex projects** where existing structural models struggle

Specialising in granites & high-grade metamorphic environments

Commercial Outcomes

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Lower drilling risk

- ✅ Drillholes oriented correctly by understanding structural geometry.
- ✅ Fewer holes miss their targets.
- ✅ Capital efficiency improves without increasing exploration spend.

Better modelling & resource estimates

- ✅ 3D models constrained by realistic structural rules.
- ✅ Withstand scrutiny from investors & auditors.
- ✅ Improves financing outcomes.
- ✅ Reduces project development risk down the line.

Efficient target selection

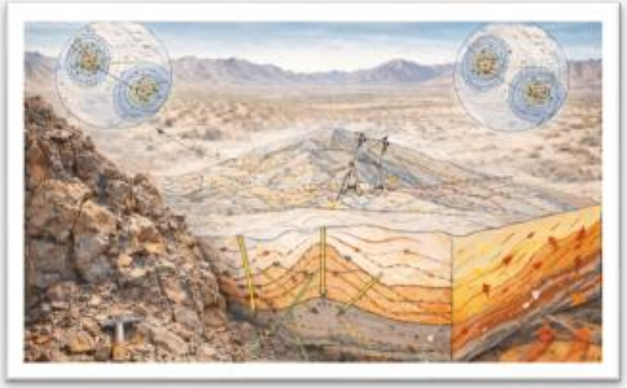
- ✅ Prioritisation of exploration targets that fit the tectonic setting.
- ✅ Early rejection of structurally implausible targets.
- ✅ Faster go/no-go decisions based on geological evidence.
- ✅ Capital spent where it has the highest probability of success.

Translating structural geology into exploration & drilling strategies

Continued support to iterate & refine structural understanding as project progresses

Key Services

1. Structural Frameworks



2. Applied to Exploration & Drilling Strategy

3. Iteration & Refinement as project progresses

Capabilities span from the orogen-scale to deposit-scale

Supporting evidence-led decision-making by reducing geological uncertainty

Full deposit-to-regional scale structural framework

Regional tectonic setting

- Critical review of existing data
- Regional datasets

Outcomes

- ✅ Realistic exploration strategy for the tectono-metamorphic environment
- ✅ Focus sparse resources into areas with the greatest chance of success

Camp-to-deposit scale

- Detailed structural mapping
- Predictive structural models
- Drilling support & recommendations

Outcomes

- ✅ Higher success rates from drilling
- ✅ Fewer missed targets
- ✅ More robust resource estimates

Specialist studies

- Statistical fracture network analysis
- UAV surveying & orthophoto / DEM interpretation

Outcomes

- ✅ Predict patterns in younger brittle structures hosting secondary mineralisation

Capability building

- Training in operationally relevant structural skillsets

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Thomas Lloyd Jones

Strategic Advice | Applied Structural Geology

Biography

👉 **Unique combination of deep technical expertise + commercial strategy consulting in the mining & exploration industry**

Mr Jones began his research career with the statistical quantification of fracture networks for oil and gas reservoirs. He then spent 4 years undertaking field-based research on the structural-tectonic setting of uranium mineralisation in the Damara Orogen, Namibia. He collaborated closely with the exploration industry throughout his time in Namibia.

Mr Jones has a further 2.5 years experience as a Senior Strategy Consultant and Market Analyst at the consulting firm Wood Mackenzie. Here, he specialised in executive-level communication and decision making, and in modelling & understanding critical mineral market dynamics, value chains, and long-term structural trends in the energy & natural resources sector. He holds an MSci degree in Geology from Durham University (UK).

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