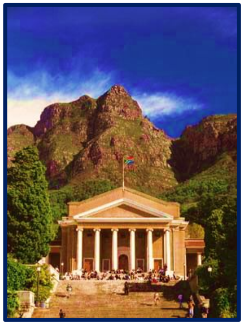

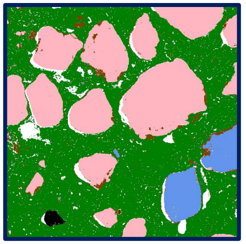

SAIMM Geometallurgy Conference 2025

Assessing the Variability in Ore Hardness and Model Transferability for a Mineral Sands Deposit

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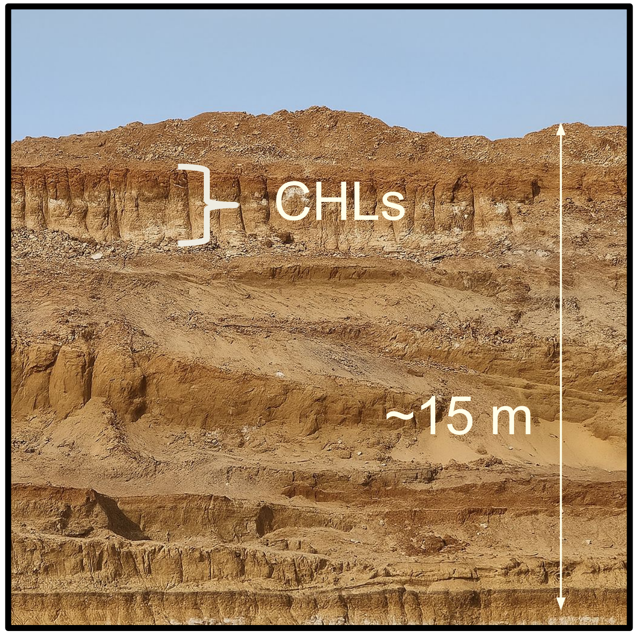
Introduction to mineral sands

- Location: Situated on South Africa's west coast
- Deposit hosts world-class heavy minerals (HMs) rutile (TiO_2), ilmenite ($FeTiO_3$) and zircon ($ZrSiO_4$)
- Unique geology: Formation of cemented hard layers ("CHLs") from normally loose sands

Philander & Rozendaal, 2015

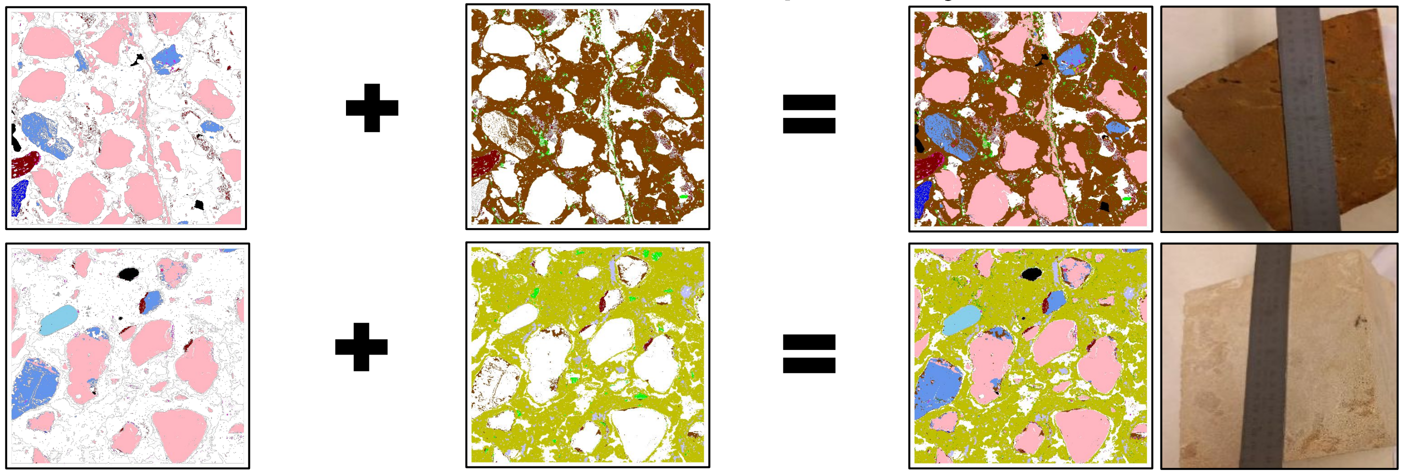


1 Open Pit Mining → 2 Primary Concentration → 3 Mineral Separation Plant → 4 Smelting

Philander, C. & Rozendaal, A. 2015. Geology of the Cenozoic Namakwa Sands heavy mineral deposit, West Coast of South Africa: A world-class resource of titanium and zircon. Economic Geology. 110(6):1577–1623. DOI: 10.2113/econgeo.110.6.1577

Mineralogy of the CHLs

- Formed as a duricrust which precipitated minerals (e.g. sepiolite, calcite, mica/smectite) cemented the sand grains and valuable minerals
- Multiple periods of ground water activity - multiple CHL with varying mineralogy
- Theory: CHLs behave like concrete – matrix minerals bring strength and hardness to the CHL, along with other factors such as texture and porosity



Al-Mg rich clay matrix
(e.g., mica/ smectite)

Ca-Mg rich matrix
(e.g., sepiolite/calcite mix)

Aggregates
(coarser grains including HMs)

Cement
(finer matrix minerals)

$1x1mm^2$ QEMSCAN false colour images (Sikushumane, 2024)

- Variation in hardness resulted in the installation of a SAG mill in 2007
- Current geometallurgical models focus on grade and recovery, with no physical hardness proxy linked to processing behavior

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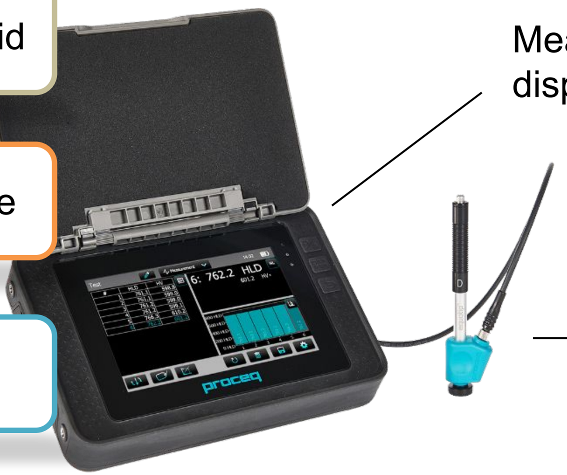
Quantifying ore hardness for this study

Leeb Hardness Tester

Portable and rapid

0.05-5 kg sample

0.8-25 mm thickness



Proceq, 2017[1]

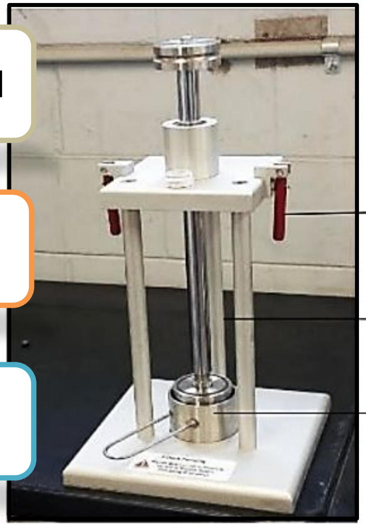
- Proxy
- Non-destructive
- Measures the ratio of rebound to impact velocity
- HLS scale: 0 (soft) – 1000 (hard)

Hardness Index Tester (HIT)

Portable and rapid

~500 g sample

22.4-19.0 mm particles



Kojovic, 2016[2]

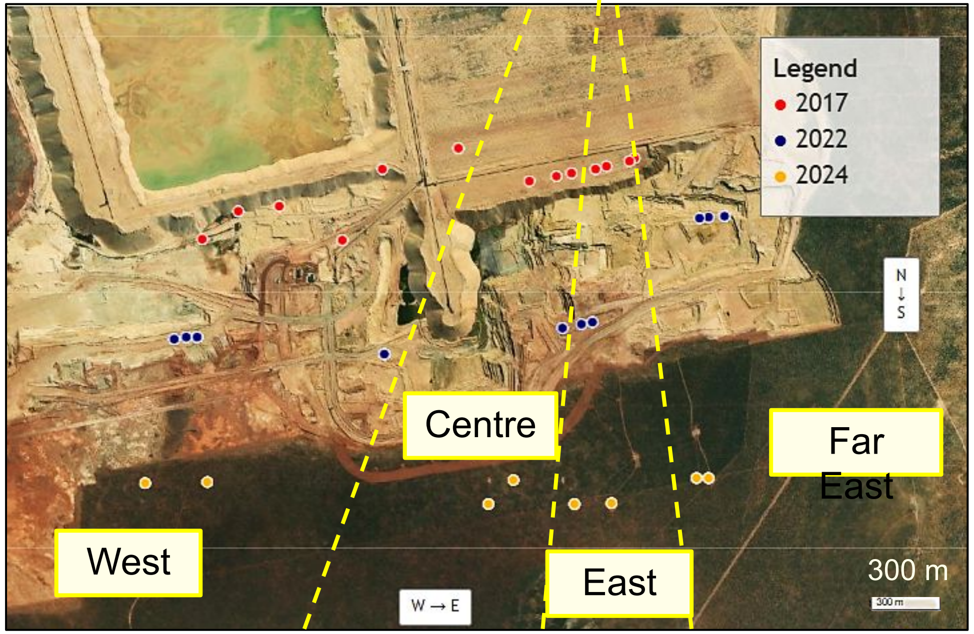
- Proxy
- Destructive
- Measures the relationship between impact energy and particle breakage
- A*b scale: <30 hard, >70 soft

1. Proceq, 2017. Equotip Portable Hardness Testing.
2. Kojovic, T. 2016. HIT-a Portable Field Device for Rapid Testing at Site. In 13th AusIMM Mill Operators Conference. Perth, West Australia. 9–16.

Study datasets: 2017, 2022, and 2024

Approach	2017 (39 samples)	2022* (43 samples)	2024 (24 samples)	Total
Type of sampling	Bulk	Selective	Bulk	-
Modelling HIT A*b				-
Bulk chemistry (XRF)	39 ✗	43 ✓	24 ✗	106
Mineralogy (XRD and QEMSCAN)		43	24	67
Leeb hardness (HLS)	19	43	24	86
Impact breakage (HIT A*b)	24	43	24	91
Mechanical strength (UCS[a])			24	24
Mechanical strength (PLT)			24	24
Grindability (BWI)			24	24
(grey)	Not measured			
(green)	Included in the analysis			
(blue)	Available, but not included in scope of presentation			

Sample distribution map showing arbitrary pit location divides (depth not represented)



Lateral variability (pit location)

Year	West (32)	Centre (19)	East (33)	Far East (22)
2017	15	3	18	3
2022	11	10	9	13
2024	6	6	6	6

** 2022 dataset from Sikushumane (2024)*

Aim and key questions

Aim:

To understand the variability in hardness with mineralogy and to test the transferability of the model developed by Sikushumane et al (submitted) across the different datasets

Key Questions:

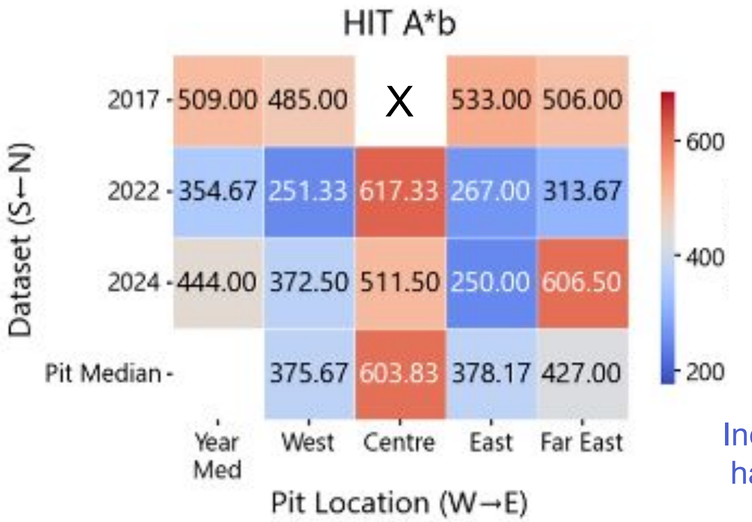
1. How do chemistry and hardness relationships differ by sampling year?

2. Can a model trained on one year predict hardness in others?

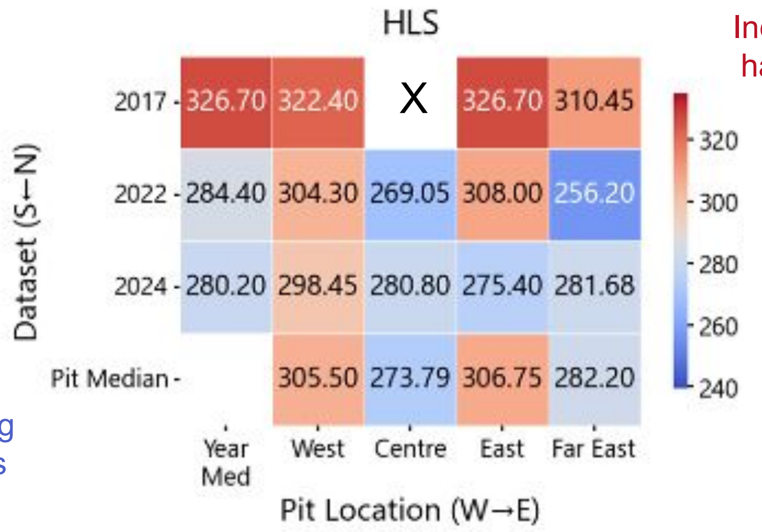
3. What geological or sampling factors explain variability?

Sikushumane, M., van der Westhuizen, A., Philander, C. & Becker, M., submitted. Development of preliminary geometallurgical proxies to predict the hardness of the cemented hard layers in a mineral sands deposit. Natural Resources Research.

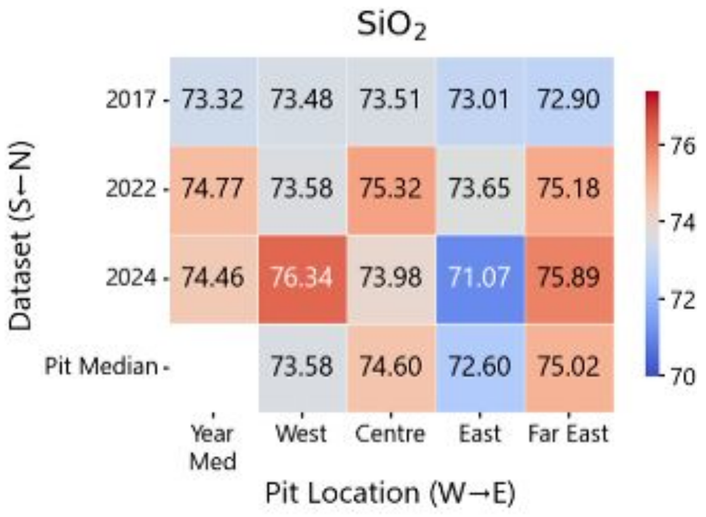
Variability across datasets and pit location

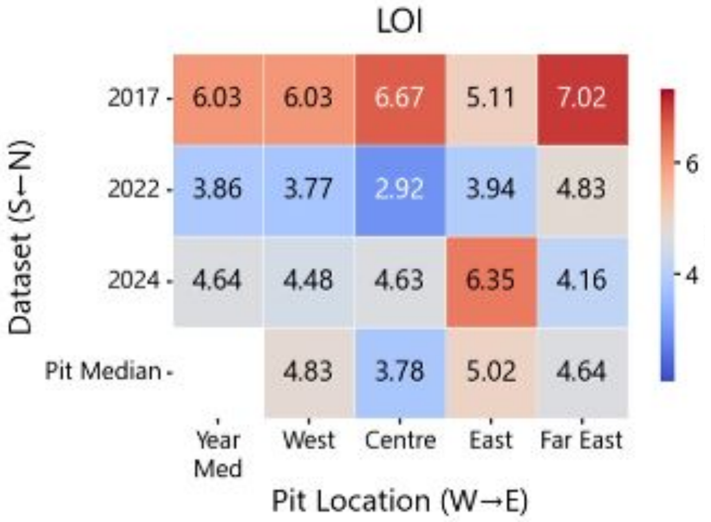


Increasing hardness



Increasing hardness





- Deposit is generally very soft.
- HIT A*b and HLS are more strongly related across pits than across years
- West and East pits are hardest; Centre pit consistently soft across years.
- Centre pit has high SiO_2 (granular quartz) and low LOI (less cementing material).

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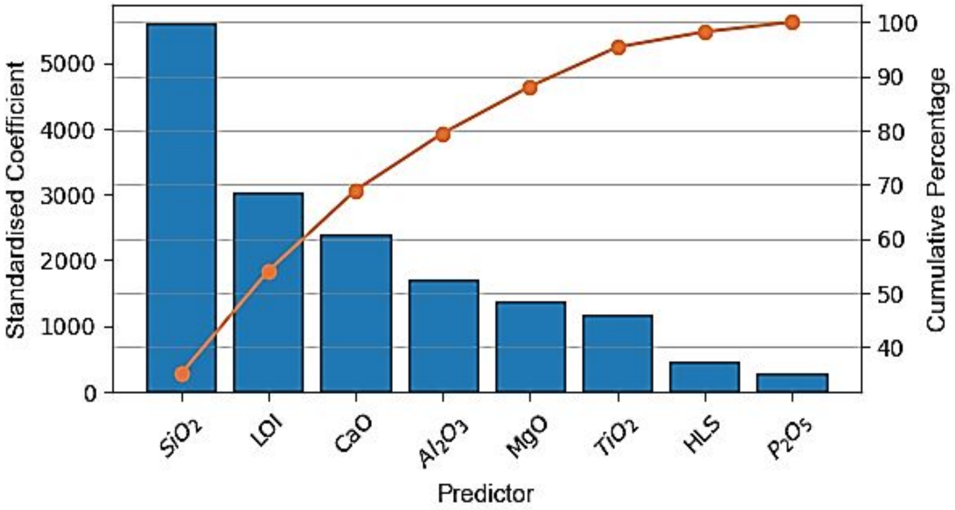
Modelling the relationship between chemistry, HLS and HIT A*b

- Initial model developed on the 2022 dataset (43 samples)
- LOI reflects the loss of volatiles like water and CO_2 from clays and carbonates during XRF analysis

$$HIT\ A*b = 1.64*10^4 - 374TiO_2 - 524P_2O_5 - 132CaO - 150SiO_2 - 318Al_2O_3 - 221MgO - 165LOI - 2HLS$$
$$R^2 = 0.80, RMSE = 114\ (root\ mean\ square\ error)$$



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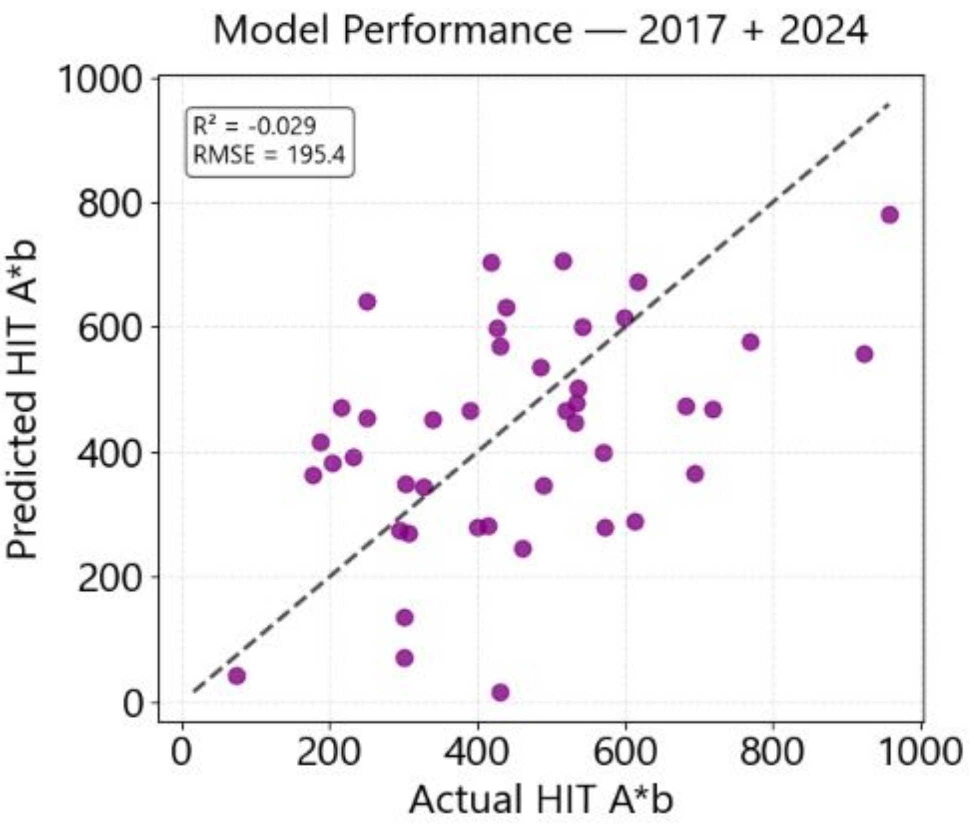
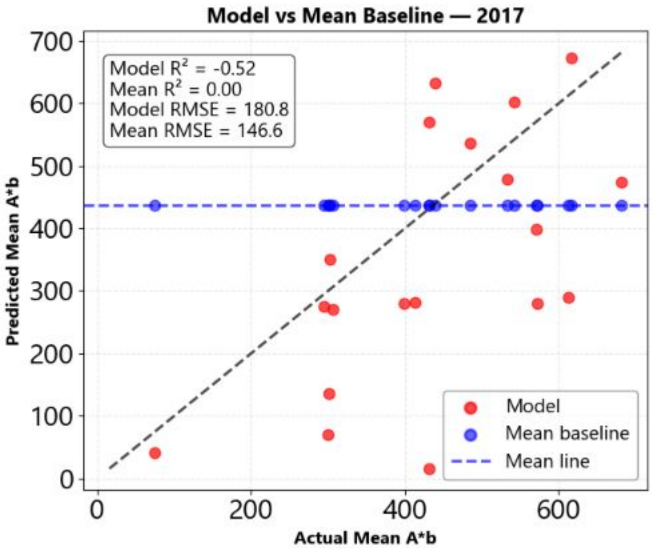
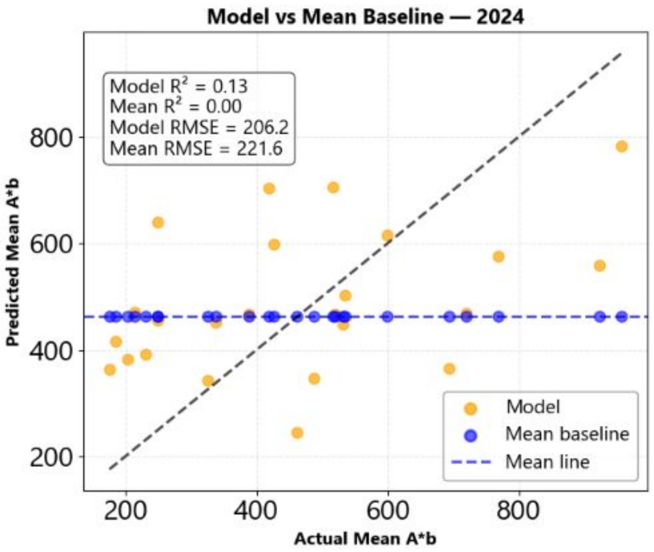
Model validation on 2017 and 2024 data







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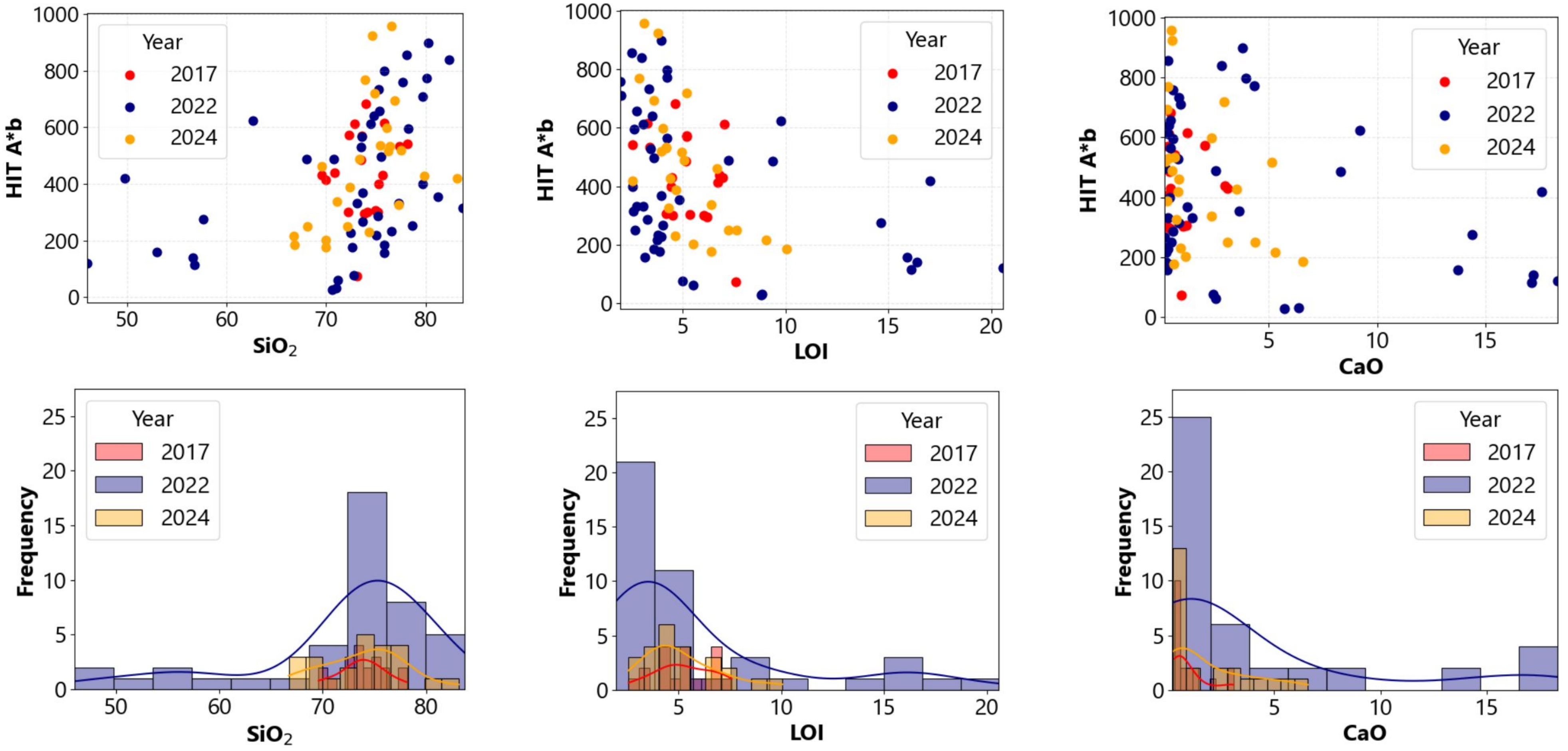
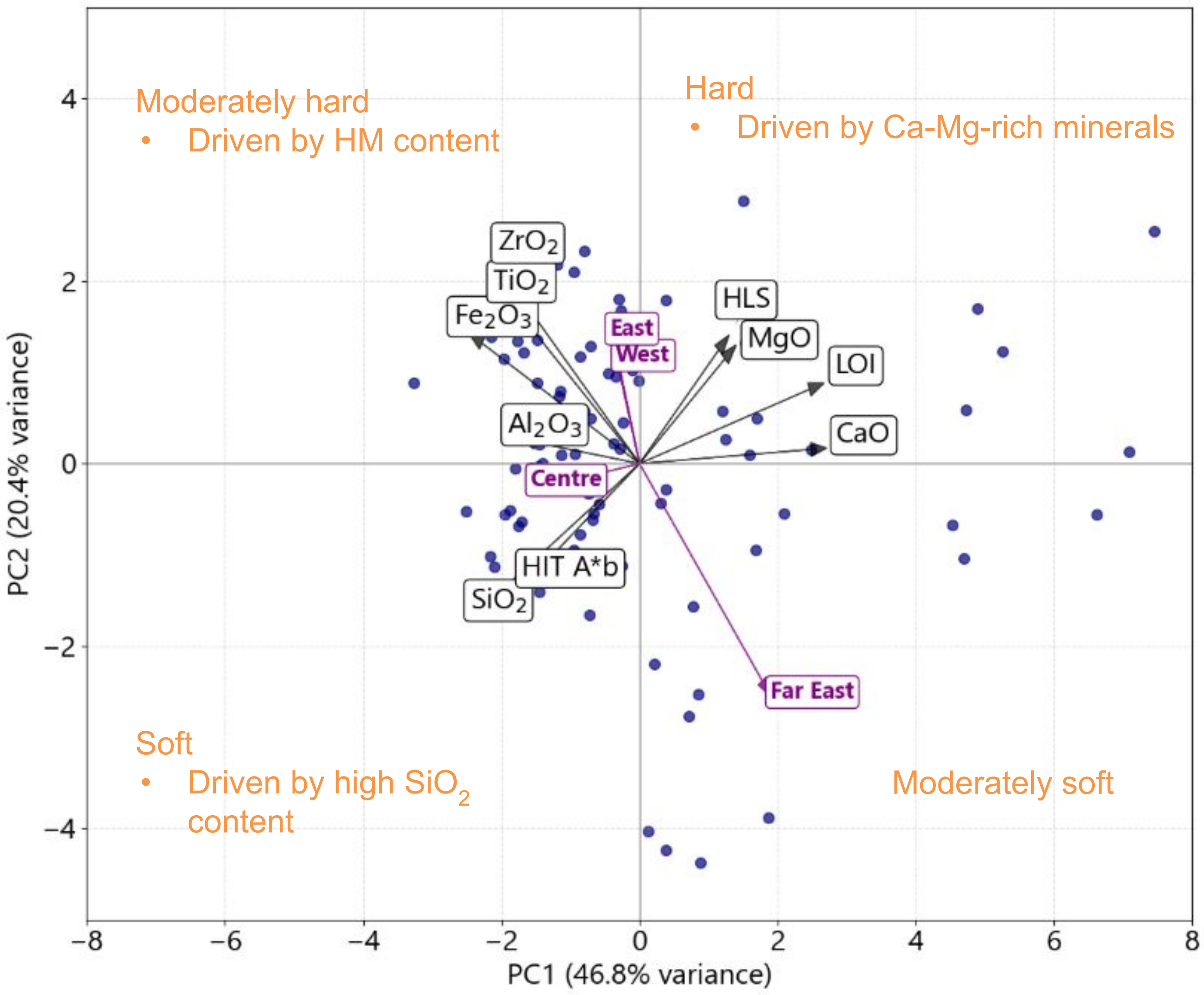
Understanding model performance: Features & Data Spread

- 2017 and 2024 data are chemically clustered, showing little of the variability needed for the model's predictions to hold

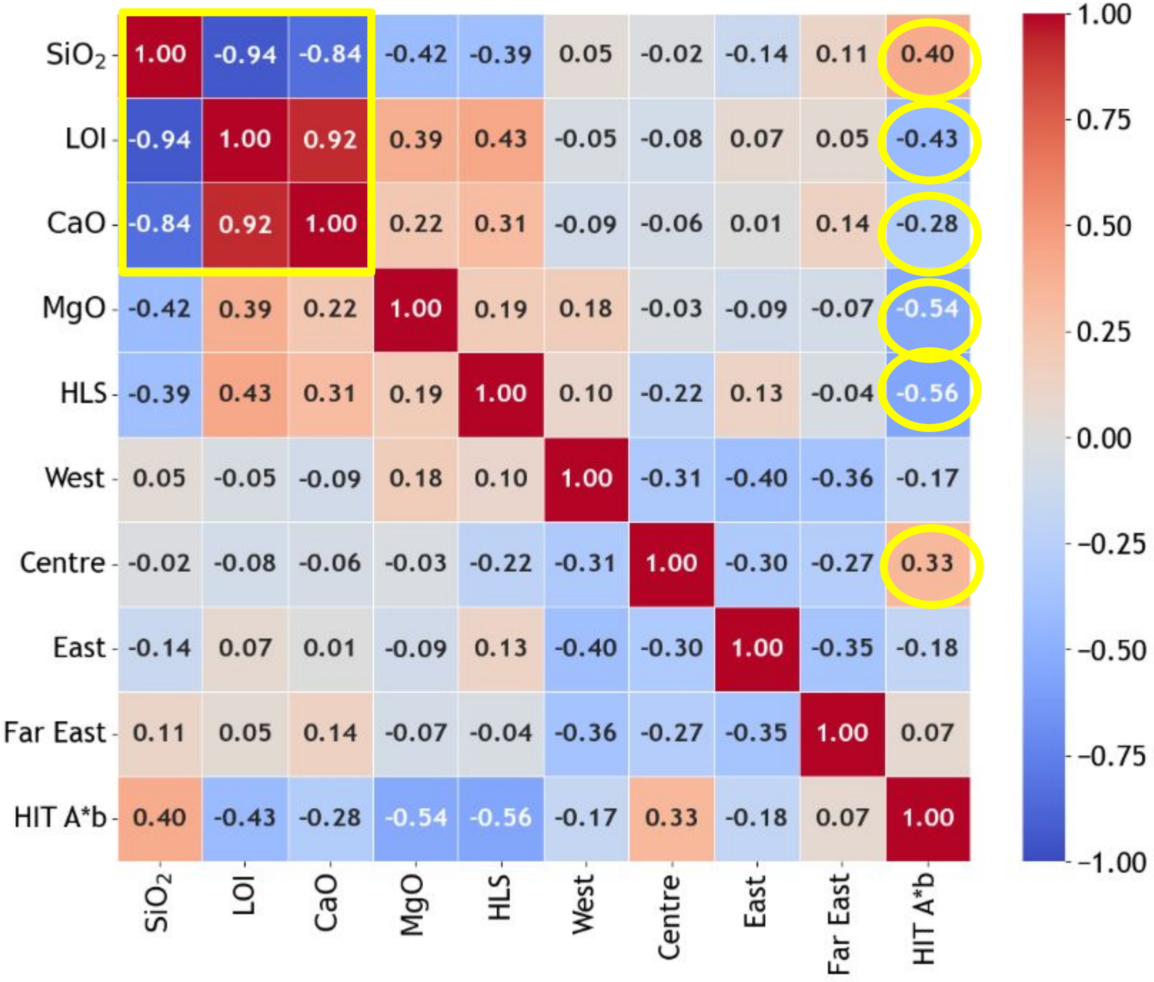


Principal component analysis (PCA)



- Reveals distinct geochemical domains
- PC1 (47%) separates "Grain-Dominant" (High SiO_2) from "Matrix-Dominant" (High CaO/LOI) ores
- PC2 (20%) separates soft Centre Pit material from hard Far East Pit material.

Moving towards improved models using combined dataset



|R|>0.21 statistically significant at 95% confidence interval for n =86

- Strongest relationship to HIT A*b is HLS followed by MgO content
- Consideration of covariance: SiO_2, LOI and CaO

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Conclusions and next steps

- Hardness is systematically controlled by a "concrete-like" grain (SiO_2) vs. cement (CaO/LOI/MgO) relationship.
- The deposit contains distinct hard (East Pit) and soft (Centre Pit) domains, revealed by PCA.
- The developed model (Sikushumane et al. submitted) captured key chemical controls but showed limited transferability across the datasets.
- The study has also highlighted that consistent sampling is crucial for reliable classification and more accurate interpretation of hardness and chemistry trends.
- Further data analysis and model refinement are needed to address correlated variables and uneven data distribution, and to explore domain-specific.

Sikushumane, M., van der Westhuizen, A., Philander, C. & Becker, M., submitted. Development of preliminary geometallurgical proxies to predict the hardness of the cemented hard layers in a mineral sands deposit. Natural Resources Research.

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Acknowledgements

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