MINERAL SYSTEMS ATLAS

1. INTRODUCTION

- GSWA delivers pre-competitive geoscience data for Western Australia that resource companies use to inform their mineral prospectivity and targeting studies.
- These geoscience data are currently delivered in many disparate databases, which commonly must then be further processed to derive exploration-relevant information.
- GSWA proposes to deliver geoscience data more effectively to our customers, via a digital Mineral Systems Atlas that distils primary data into formats more immediately applicable to mineral exploration.

2. CONCEPTUAL BASIS – MINERAL SYSTEMS

Mineral prospectivity studies endeavour to map conceptual favourability for ore genesis (e.g. Fig. 1).

There are two common approaches:

Data-driven - Spatial correspondences are sought between favourable geological criteria empirically determined from their geostatistical correlations with known mineral deposits.

Knowledge-driven - Spatial correspondences are sought between geological proxies for critical mineralizing processes defined from an understanding of the metallogeny of mineral systems.

Both approaches require similar georeferenced geological data, but a knowledge-driven approach is necessary to evaluate mineral prospectivity in "greenfields" regions where mineral endowment is unknown.

GSWA therefore adopts this approach, using the **Mineral Systems** concept as a basis for developing the Mineral Systems Atlas (e.g. Wyborn et al., 1994; McCuaig et al., 2010).

A Mineral System comprises all geological processes that generate mineral deposits during a particular critical window of time (a mass- and energy-flux event), and then ensure their preservation.

For a region to be prospective for mineral deposits now, it must necessarily show all the **critical ingredients** (Fig. 2):

- a **SOURCE** for metals and transporting fluids (mass) and system driver (energy)
- a **PATHWAY** along which metals and fluids could pass from source to sink
- a physical and/or chemical throttle to **TRAP** metals at the sink
- **PRESERVATION** of mineralization in the crust up to the present time.

If **any** are absent from a region, its mineral prospectivity will be low.

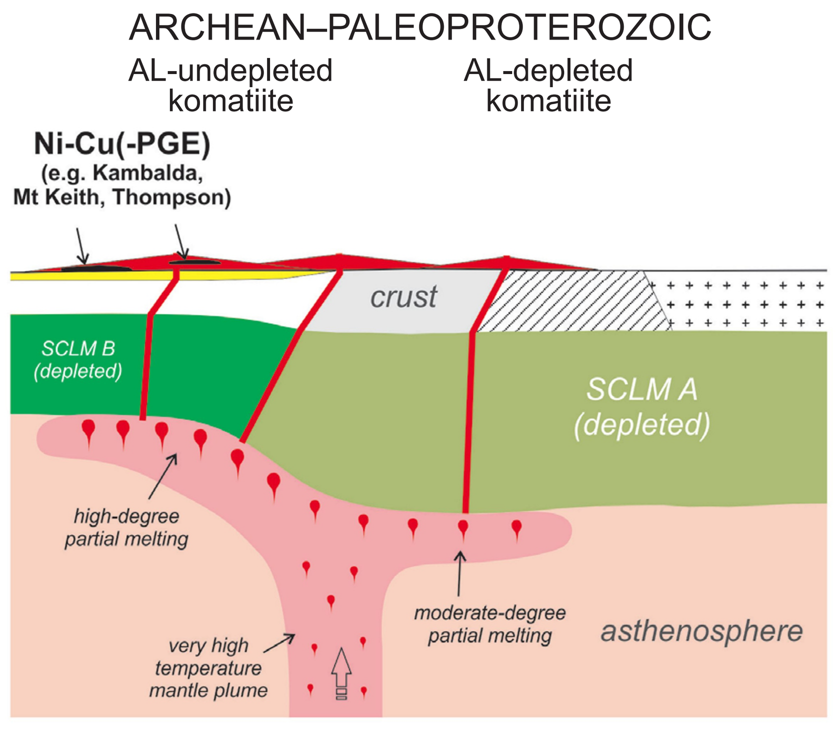


Figure 3: Conceptual model of komatiite-hosted Ni(-Cu-PGE) sulfide ore-forming systems, based on a synthesis of information from studies of nickel sulfide deposits globally. SCLM A (depleted) and SCLM B (depleted) represent separate blocks of sub-continental lithospheric depleted mantle (after Dulfer et al., 2016).

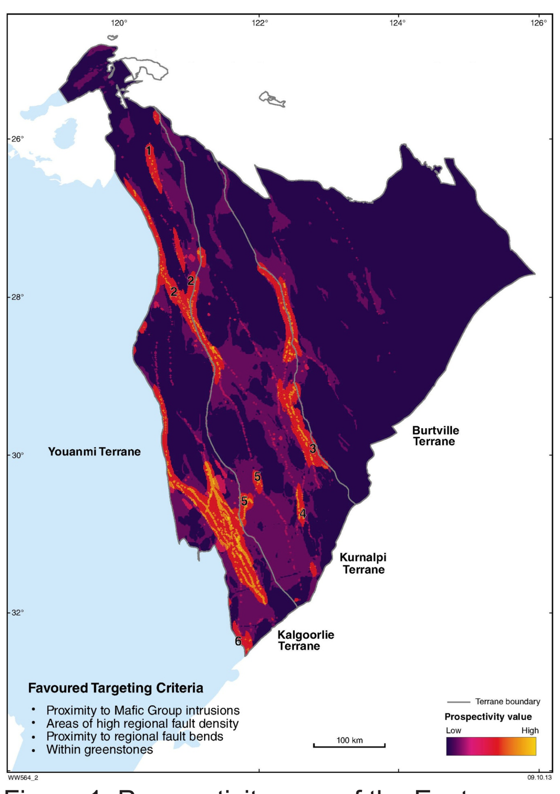


Figure 1: Prospectivity map of the Eastern Goldfields Superterrane based on the four most-favoured targeting criteria (after Witt et al., 2013).

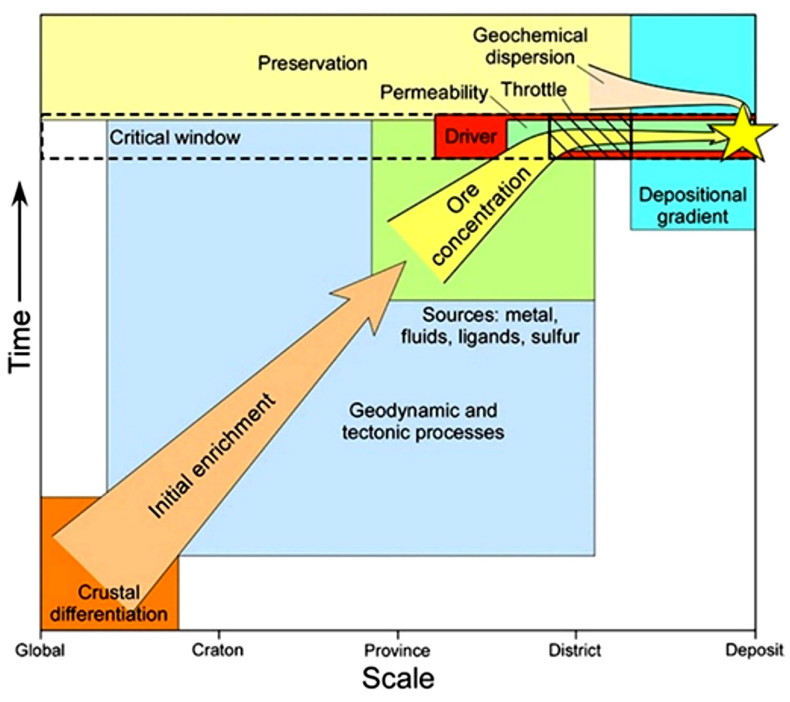


Figure 2: Scale–time diagram illustrating the concept of a mineral system (SOURCE: Geoscience Australia)

3. CREATING THE MINERAL SYSTEMS ATLAS

The "Mineral Systems Atlas" will comprise a suite of GIS layers that map the distribution of observable **geological proxies** for the critical ingredients of mineral systems.

For practical purposes, the specific contents of these layers are determined by undertaking Mineral Systems Analyses for different classes of mineralization (deposit types), as defined in Geoscience Australia's "Geodynamic and tectonic classification of mineral systems" (Fraser et al., 2001).

A Mineral Systems Analysis identifies:

- the **constituent geological processes** by which the critical ingredients operated
- the geological features **– or targeting elements -** by which each constituent process might have been manifested
- the **mappable geological proxies** that represent the targeting elements.

Each Mineral Systems Analysis draws on relevant expert knowledge from publications and collaboration.

Each proxy is defined by an "algorithm" for a particular combination of geoscience data.

These GIS layers then constitute the digital "pages" of the Mineral Systems Atlas.

Generating geological proxies — an illustrative example

Creation of the Mineral Systems Atlas is here illustrated using komatiite-hosted Ni sulfide deposits (Fig. 3), a relatively well understood subset of the orthomagmatic mineral system.

A mineral systems analysis yields more than 50 geological proxies for the critical and constituent metallogenic processes at different scales (regional, camp, deposit; e.g. Fig. 4).

Each proxy map is created by querying and combining data in a particular way (the "algorithm"). "Algorithms" can vary in terms of ease of generation from relatively simple to rather complex (see Box)

Proxies are prioritised based on robustness, applicability at broader scales of exploration, and ease of generation. For instance, the four top-ranked proxies for komatiite-hosted Ni-sulfide deposits are:

- komatiite occurrence map (indicates a fertile SOURCE at regional scale (e.g. Fig. 5c)
- komatiite facies map (used to identify magma channels - the PATHWAYS and TRAPS at camp to deposit scale)
- whole-rock geochemical abundance and ratio maps (e.g. MgO content, Mg#, element proxies for crustal contamination; also indicators of PATHWAYS and TRAPS at camp to deposit scale)
- mineral chemistry maps (e.g. Ni content in olivine, Ni in chromite; indicators of proximity to TRAPS at the camp to deposit scale).

Critical Process (generic)	Critical Process (specific)	Constituent process *What are the processes that control Critical Process?*	Targeting element *How could we target each process?*	Mappable Proxy and "Algorithm"	Scale of usefulness	Ease of generating the derived product	Ranking of the derived product
SOURCE fluids, metals, energy	Komatiite formation	**High-degree mantle melting** to produce ultramafic and komatiite magmas plus felsic volcanic rocks (i.e. a bimodal volcanic rock association)	**Thick, abundant, laterally extensive ultramafic rocks** with the potential to produce komatiite flows	**Komatiite occurrence map** = WA solid geology + drill hole database **Ultramafic occurrence map** = WA solid geology + drill hole database **Komatiite occurrence map** = WA solid geology/ultramafic units - komatiite units + drill hole database + WACHEM database/Mg, Ni, Cr data/Mg>18 wt% map-Ni>0.1 ppm map-Cr>0.1 ppm map + WA geophysics/ Gravity highs + magnetic highs + Hyperspectral data/olivine, serpentine, MgOH mineral abundances + WAROX + WAMEX/ talc occurences **Komatiite thickness map** = WA solid geology map/komatiite occurrence map+ WA geophysics/gravity+ Gole komatiite facies map + **Drill hole database**	Multi-scale	Easy	High
			Bi-modal rocks association	**Felsic volcanic rock occurrence map** = WA Solid Geology **Quartz andesite occurrence map** = WA Solid Geology/TTG-TTD rock occurrence map **Rhyolite occurrence map** = WA Solid Geology/TTG-TTD rock occurrence map **Dacite occurrence map** = WA Solid Geology/TTG-TTD rock occurrence map **Felsic volcanic (andesite, rhyolite, dacite) rock age map** = WA Solid geology + geochronology	Cratonic to terrane-scale	Easy	High
			Association with thick mafic rock sequence, indicating extensive, high-degree melting	**Mafic occurrence map** = WA solid geology **Mafic thickness map** = WA solid geology map/mafic occurrence map+ WA geophysics/gravity **Mafic classification map** = WA solid geology/Mafic occurrence map + WACHEM database/Na, K, Fe, Mg data/Tholeiitic, calc-alkaline, and komatiitic basalt magma series AFM plot **Basalt classification map** = WA solid geology/basalt occurrence map + WACHEM, Barnes database/ High-Thorium siliceous basalt (Komatiite relationship) - Low-Thorium basalt (Archean plume head)	Cratonic to terrane-scale	Easy	Moderate
			Archean/Proterozoic granite greenstone terranes where komatiites are most common, but also consider possible younger ages	WA Solid geology + geochronology data sets + ENS database = **Archean and Proterozoic rock age map** Geochronology data sets + WA solid geology/Komatiite occurrence map + ENS database = **Komatiite rock age map**	Multi-scale	Easy	Moderate

Figure 4: Excerpt from a Mineral Systems Analysis for komatiite-hosted Ni-sulphide deposits. In the "Mappable Proxy" column, bold black text denotes the map product, and bold blue text denotes the source database(s) to be queried.

BOX: Algorithms for generating geological proxy layers

The Mineral Systems Atlas will deliver geological proxy maps for critical and constituent metallogenic processes. Each proxy is created by querying and combining geoscience data according to a particular conceptual "algorithm", which can vary from relatively simple to rather complex.

For instance, many (the majority?) of komatiite occurrences in WA can be mapped directly from the GSWA solid geology database via a simple query:

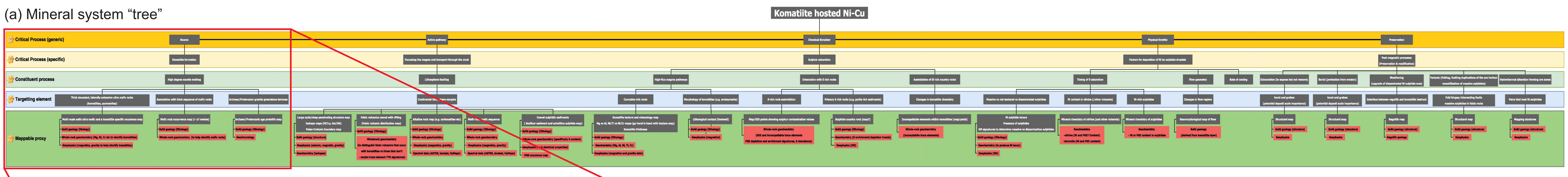
> **WA Solid Geology** where rock type = komatiite

However, the solid geology data also include many undifferentiated ultramafic rocks that might be komatiites, and previously unrecognised komatiites may also be recorded in other databases. To identify these requires a more complex query:

> **WA Solid Geology** where rock type = undifferentiated ultramafic AND/OR **WAROX + Exploration drill hole data** where rock type = ultramafic OR komatiite OR talc-rich OR serpentine-rich OR komatiite textures AND (**WACHEM** Mg, Ni, Cr data where Mg>18 wt% AND Ni>0.1 ppm AND Cr>0.1 ppm AND/OR **WA Geophysics** = coincident gravity + magnetic highs AND/OR **Drill hole hyperspectral data** where minerals = abundant olivine OR serpentine OR MgOH minerals)

It is a non-trivial task to generate geological proxy maps using complex queries of this sort, but one that GSWA plans to streamline as part of this project.

(a) Mineral system "tree"



(b) A constituent process for "SOURCE", and some mappable proxies

(c) Some geological proxy maps

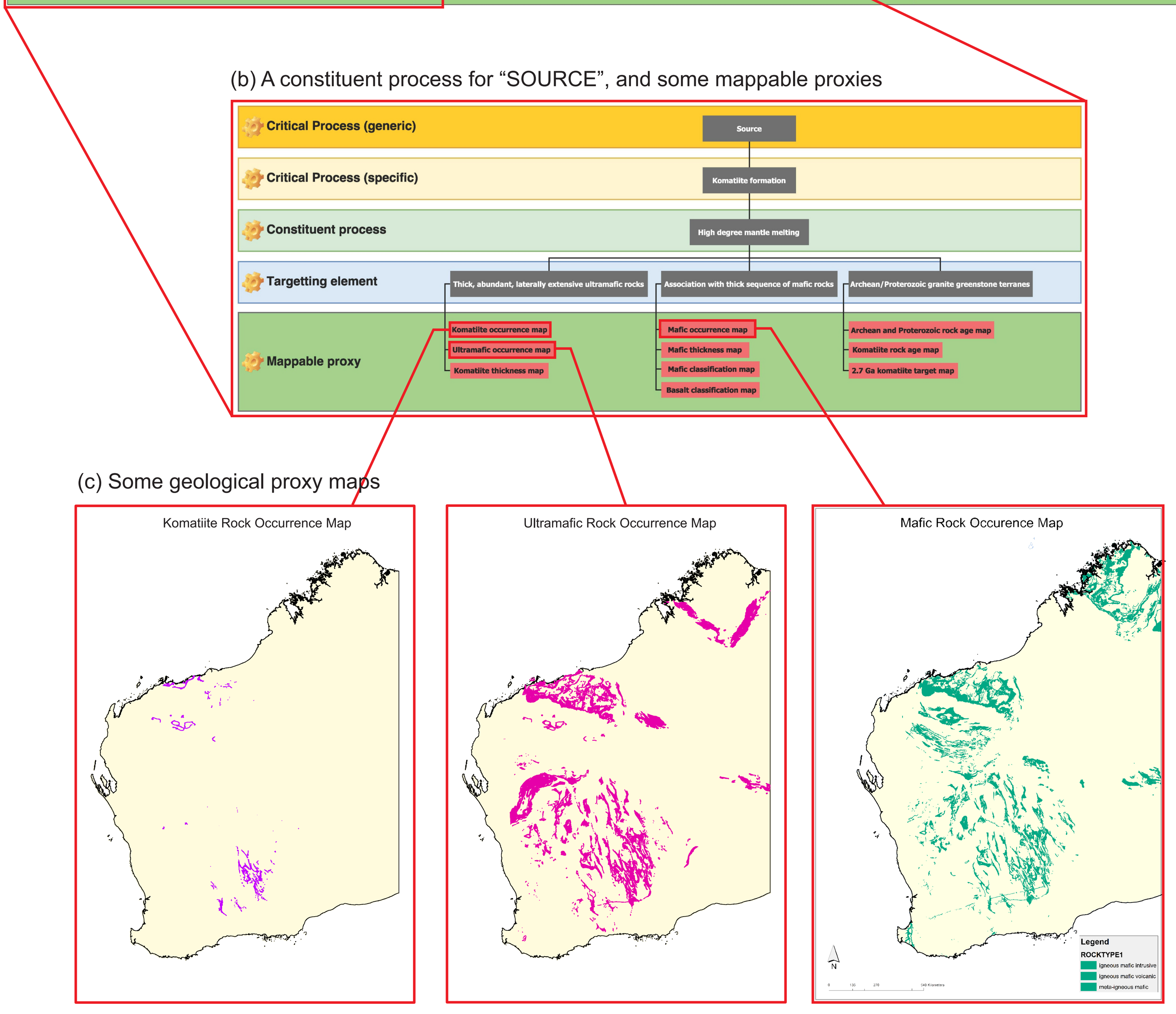


Figure 5: Schematic depiction of the proposed interactive, modular, hierarchical Mineral Systems Atlas, in this instance illustrating the "segment" for komatiite-hosted Ni-sulphide deposits.

4. ATLAS FORMAT

The Mineral Systems Atlas will deliver digital geoscience data maps that mineral explorers can use for any type of mapping-based mineral prospectivity evaluation of Western Australia.

It will be intuitive and interactive, allowing users to select and download only required data layers.

Its modular and hierarchical design (e.g. Fig. 5a) will readily permit the addition of new mineral systems and new geological proxy layers (there will be much commonality).

It will integrate legacy "proxy" maps developed for particular orogens and deposit classes (Aitken et al., 2014; Dulfer et al., 2016; Joly et al., 2013, 2014; Lindsay et al., 2015, Occhipinti et al., 2016).

Its structure will permit users to trace the relationship between primary data and derived "proxies".

5. WHITHER NOW?

The portal for the Minerals Systems Atlas is currently under development.

Mineral Systems Analyses are well-advanced for a number of priority mineral deposit classes (komatiite-hosted Ni-sulfide, orogenic Au, BIF-hosted iron ore); other systems will be systematically evaluated.

The Atlas will be progressively populated with state-wide, initially bespoke "pages" (proxy data layers) defined and created by GSWA.

The longer term goal is to develop and embed in the Atlas an online query tool that:

- generates the Atlas "proxy layers" on the fly (thereby ensuring that these are automatically updated whenever new data become available)
- allows users to interactively derive any combination of geoscience data and deliver this as a GIS layer, without needing to directly "see", merge or otherwise manipulate the underpinning databases (Fig. 6).

GSWA is concurrently reviewing all its databases to ensure that these are capable of capturing the required data, and that these data are being collected.

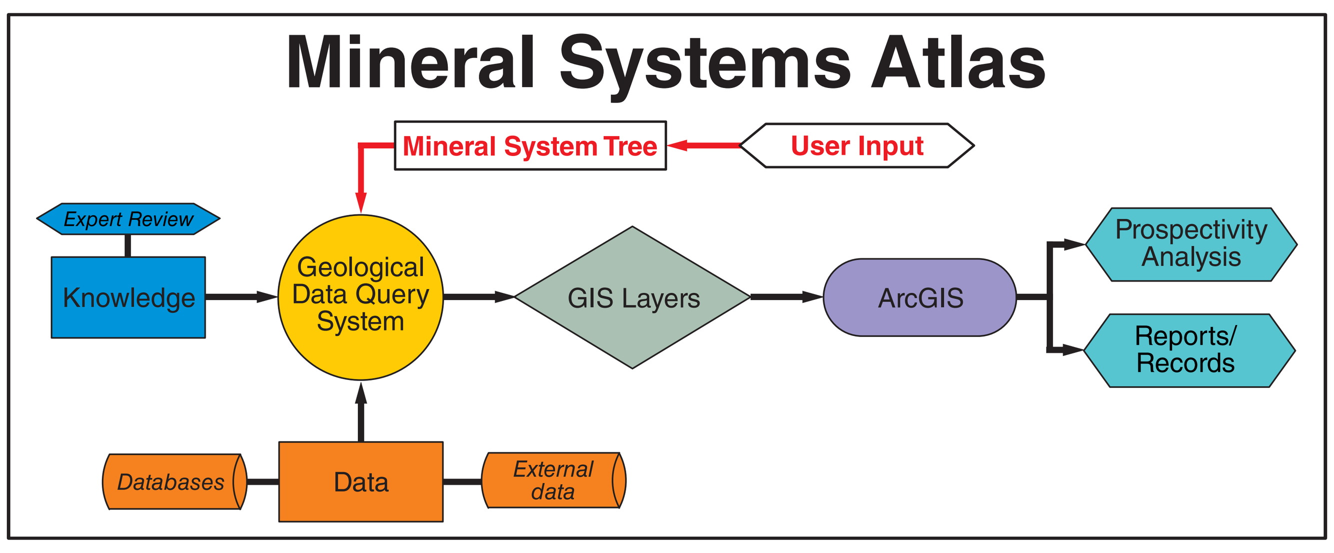


Figure 6: Ideal future structural model for the Mineral Systems Atlas, allowing users to extract any combination of GSWA geoscience data as a GIS layer

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