Empirical Mineral Systems Targeting for Base Metals in Sedimentary Basins

Neal Reynolds & Peter Muhling
CSA Global
The clear conclusion is that, for the global mining industry to sustain itself, it either needs to reduce production, or increase the exploration spend, or it needs to be much more efficient at discovery” …..

- Increasing demand, reducing production is not an option
- Increased efficiency at discovery required

Richard Schodde 2017
Zn for Future Generations

Richard Schodde 2017

Zn metal discovered

Zn metal discovered (adjusted for estimated Zn metal that has been or will be produced), production, and predicted future discovery
Pb for Future Generations

Richard Schodde 2017

Pb metal discovered

Pb metal discovered (adjusted for estimated Pb metal that has been or will be produced), production, and predicted future discovery
Mineral Systems Targeting

Analogous to petroleum approach but systems with far greater complexity

Mineral Systems defined as

‘all geological factors that control the generation and preservation of mineral deposits’  

Wyborne et al. 1994

➢ pmdCRC Mineral Systems project
➢ Predictive mineral discovery – the need for a new approach to targeting under cover
➢ Understand the entire system at all scales to facilitate modelling and targeting

pmdCRC Mineral Systems 5 Questions 2008
Zn-Pb Mineral Systems

Zn-Pb Deposit Styles & Models – a Classification Nightmare!

Multiple overlapping terms and acronyms – e.g. SHMS/Sedex/CD, Irish-type/MVT, CRD/Manto

Broadly group:

- "Magmatic arc deposits" – CRD/skarn, diatreme & epithermal
- "Basinal deposits" – VHMS, SHMS, BHT, Irish-type, MVT, Cobar-type, Kipushi-type

Continuums & Hybrid Deposits especially in basinal systems, e.g.:

- VHMS–Epithermal – back-arc (e.g. Eskay Creek)
- SHMS–VHMS – passive margins to complex back-arc basins (e.g. Rammelsberg, Iberian Pyrite Belt, Rosh Pinah)
- SHMS–Irish-type–MVT – extension to inversion to compression

Misfits, what about, for example, Coeur d’Alene, Huize, Bawdwin, Abra?
Principal source of Zn and Pb and important source of Cu

- SHMS, VHMS, BHT, IRT, MVT, ‘Cobar-type’, ‘Kipushi-type’
- Sedimentary Copper, VHMS

Also important for Fe, Mn, U, Au and many other commodities

SHMS are dominant in production, and from fewer deposits

(Data source S&P Global Market Intelligence, 2017)
Basinal Mineral Systems

SHMS deposits – the holy grail for Zn explorers

- Biggest and most economically attractive deposits, especially if metamorphosed
- **Rampura Agucha**, the world’s biggest producer, **Red Dog, Mt Isa, McArthur River/HYC, Sullivan, Howards Pass, Macmillan Pass**, etc
- Last discoveries
  - **Century** 1990
  - **Citronen Fjord** 1993
  - **Sopokomil** 1998
  - **(Teena)** 2013, first drilled in 1976

(Data source S&P Global Market Intelligence; 2017)
SHMS deposits – the holy grail for Zn explorers

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Strata-bound or stratiform, sulphide-rich Zn-Pb-(Ag), deposits in siliciclastic-dominant basinal sequences

End product of hydrothermal systems within sedimentary basins

Partial continuums to VHMS and Irish-type systems

SHMS mineral systems involve:

- Extraction of metals from basin sediments ± basement by circulating basinal brines
- Transport and focus of metal-bearing brines by structural and formational aquifers, and
- Deposition in a reducing site with an available source of sulphur and sulphate reduction
Empirical Mineral Systems approach – a contradiction in terms?

The complexity of mineral systems supports a heuristic and empirical targeting approach that incorporates mineral system understanding over purely theoretical models and modelling.

**Basin Mineral Systems as an example**

- Empirical basin-, trend-, and deposit-scale criteria are based on observation in multiple basins.
- Support from mineral system framework, even if details of complex processes are not fully understood.
- Criteria are defined as **Essential**, **Prevalent**, or **Favourable**.
- Basins are screened for fertility based on criteria related to **Source**, **Trigger**, **Focus**, **Trap**, and **Process**.
- ‘**Plays**’ are defined and prioritised along prospective trends or fairways based on **Focus** and **Trap**.
- **Plays** defined at a scale that can be identified with available data and tested for concept validity.
- Deposit-scale targeting integrates direct alteration and deposit signature.

*Improve identification of fertile basins and effectiveness of targeting within basins.*
What are the shared characteristics of known SHMS basins ...

.... and how do they fit within Mineral Systems understanding?

- **Isa & McArthur Basins** – Late Palaeoproterozoic
- **Aravalli Supergroup** – Late Palaeoproterozoic- Early Mesoproterozoic
- **Belt-Purcell Basin** – Early Mesoproterozoic
- **Selwyn Basin** – Cambrian-Devonian
- **Franklinian Basin** – Cambrian-Devonian
- **Rheno-Hercynian Trough** – Devonian
- **Kuna Basin** (Brooks Range) – Mississippian
- **Barisan Range**, Sumatra – Carboniferous-Permian
Basin type, tectonic setting and evolution

➢ Many types of basins, but SHMS only occur in basins with very specific features
Basin type, tectonic setting and evolution

- **Intracratonic rift-sag basins**, may or may not evolve to a passive margin
- Implies major **basin architecture faults**
- Common **back-arc setting** with significant volcanism; transitional SHMS-VHMS, e.g. Rheno-Hercynian, Iberian Pyrite Belt
- **Long-lived**, commonly with multiple rift/sag cycles; e.g. major extensional events affecting established passive margin basins (Isa Superbasin, Selwyn Basin)

Basin fill, structural architecture, and heat flow

Doust & Sumner, 2007
Basin-scale Criteria

Basin type, tectonic setting and evolution

Aravalli; Sharma et al. 2004

Rheno-Hercynian; Franke, 2000

Selwyn Basin Goodfellow & Lydon, 2007

Selwyn Basin, Cecile et al. 1997

Selwyn multi-cycle rift-sag in distal back-arc setting?

Aravalli rift to passive margin, and collisional inversion

Rheno-Hercynian passive margin of Rheic Ocean
Basin-scale Criteria

Basin type, tectonic setting and evolution

Isa-McArthur polycyclic rift-sag to passive margin in distal back-arc setting

Isa Superbasin; Gibson et al 2016
Basin-scale Criteria

Basin type, tectonic setting and evolution

Sears et al., 2004

Belt-Purcell intracontinental rift without passive margin evolution
Basin type, tectonic setting and evolution

- Kuna Basin Devonian to Jurassic passive margin
- Reworked in Cretaceous fold and thrust belt
- Overlies earlier ‘Franklinian’ passive margin basin

Young, 2004

Moore et al., 1994
Basin-scale Criteria

Basin type, tectonic setting and evolution

➢ Lower crustal plate of rift

Evolution of rift linkages and accommodation zones in low strain and high strain settings

Structural architecture and plumbing

Schematic geometry of compartmentalised rift with alternating polarity (upper plate and lower plate)
Basin Architecture

- Major basin-architecture fault zones originate at rift stage and affect sag phase sedimentation.
- Inherited as lithostratigraphic/lithofacies boundaries and structural domain boundaries; may be reactivated as thrust zones.
- Accommodation zones, relays, and basin transforms initially formed in rift; control basin palaeohighs and sub-basins in rift and sag phase.

Structural architecture and plumbing
Basin-scale Criteria

Basin type, tectonic setting and evolution

➢ Rift-sag evolution is fundamental; polycyclic evolution is common

➢ **Tectonic event** during sag phase

➢ Extension or inversion event

Nuna break-up, Idnurm (2000)

Multiple cycles of the Isa Superbasin
Betts & Lister, 2002

Trigger/driver for fluid-flow events
Basin-scale Criteria

Basin age and palaeogeography

- **<2.2 Ga** – post Great Oxidation Event
- **1.8 to 1.4 and 0.8 to 0.3 Ga** empirically favourable; correlates with intervals of supercontinent rifting and break-up
- **Anoxia events** related to lithospheric/ hydrospheric interaction during break-up

Prevalence of rift-sag basins; sediment & basin brine chemistry
Basin age and palaeogeography

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- **Low-latitude setting**; proxies include carbonate platforms and evaporites

Prevalence of rift-sag basins; sediment & basin brine chemistry

Leach et al., 2010
Basin scale and duration

- **Linear extent of at least 500 km** and indications for original extent >1000 km.
- **Original width of +100 km**; e.g. inverted Batten Trough and Walker Trough
- **Rift burial to >4 km**
- **Typically >10 km rift sequence, sag-phase 0.5 to 5 km**
- **Duration at least 50 Ma** (rift and sag) but commonly much longer; Selwyn and Isa **multi-cycle basins ±200 Ma**

Large source volume heated to c. 150-250°C for diageneric release of metals and extraction into saline brines

Source rock volume & maturity; fluid-system scale; trigger events
Rift fill

- Immature feldspathic sandstone and polymictic conglomerate, typically evolving to turbiditic wackes
- Evaporites may be present; thick evaporites and quartz-haematite red-beds are empirically unfavourable
- Volcanics and/or intrusives in the rift sequence; intraplate continental or back-arc

<table>
<thead>
<tr>
<th>Belt Basin</th>
<th>Rheno-hercynian</th>
<th>Selwyn Basin</th>
<th>Mt Isa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence in trough (NB not at edges)</td>
<td>Siliciclastic Turbidites Reducing</td>
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</tr>
<tr>
<td>Thickness</td>
<td>&gt; 6km</td>
<td>&gt;4 km</td>
<td>&gt; 3 km</td>
</tr>
<tr>
<td>Volcanics</td>
<td>None known-base not exposed</td>
<td>Acid-intermediate</td>
<td>Basalt</td>
</tr>
</tbody>
</table>

Source metal budget and chemistry; heat flow
Basin-scale Criteria

Fluvial Sandstone, McArthur Basin

Basal arkosic conglomerate, Mt Guide Quartzite, Mt Isa Western Succession

Volcanic Sandstone, Eastern Creek Volcanics, Mt Isa Western Succession

Red Siltstone, Windermere Supergroup, Selwyn Basin

Turbiditic wacke – Belt Basin
Sag fill

- Dominated by fine-grained siliciclastics
- Significant reduced facies: carbonaceous shales, dolomitic shale, calciturbidites
- Evidence of stratified basin anoxia may occur – phosphate, manganese, barite
- Carbonate-bearing rocks; reduced dolomitic shales & calciturbidites
- Volcanics and intrusives common, including thin tuffs; become volumetrically significant in transitional back-arc settings

Trap composition, chemistry; heat-flow
Barney Creek Formation, McArthur River

Moondarra Siltstone Mt Isa

Tuff horizon in carbonaceous dolomitic siltstone, Mt Isa

Hangingwall distal calciturbidites; Sopokomil host sequence

Wissenbach Shale Goslar Trough

Sullivan grey argillite and calcareous micro-turbidite; Lydon, 2007
Belt-Purcell Basin

- Reduced sediments in upper rift sequence
- Moyie sills in upper rift sequence
Platforms

- Important shelf carbonate rocks
- Evidence of evaporites or evaporative facies, including vanished evaporite indicators
- May also be volcanics in adjacent platform, e.g. Mackenzie platform
- Common Irish-type or MVT mineralization on platform (e.g. Selwyn /Mackenzie; Citronen Fjord/Polaris)

Basin brine chemistry; trap for Irish-type deposits

Warren 2006
Meggen platform: shelf-basin paleogeography – Mueller, 2005

Belt-Purcell Basin; Lydon 2007
Mineralization and alteration

- Occurrences of Zn-Pb mineralization of any style in the basin or platform
- Consistent Pb-isotope signature and broadly conformable
- Dolomitisation events on platform
- Hydrocarbons in basin or platform

Large-scale basinal fluid-flow event; trap chemistry

Ferroan dolomite, McArthur Basin

Goodfellow, 2009
Mineralization and alteration

- Occurrences of Zn-Pb mineralization of any style in the basin or platform
- Consistent Pb-isotope signature and broadly conformable
- Dolomitisation events on platform
- Hydrocarbons in basin or platform
- Iron-carbonates and pyrite in sag phase sequences
- Barite in sag-phase sequences

Large-scale basinal fluid-flow event; trap chemistry
Mineral system synthesis

**Source**
- Thick feldspathic and lithic rift sequences – voluminous fertile source
- Evaporative shelf – brine generation

**Trigger**
- Tectonism in sag phase; extensional or early inversion

**Focus**
- Basin architecture faults – fluid pathways
- Accommodation zones – fluid-gathering onto basin palaeohighs

**Trap**
- Reduced sag-phase carbonates ±hydrocarbons ±barite
- Thickness and burial – source maturity for diagenesis and metal extraction

**Process**
- High-heat-flow basin with volcanics – enhances source maturity
- Pb-isotopes, mineralization and alteration – large-scale fluid flow event
Practical application – from first principals

➢ Rift-sag basins with major structural control can be identified from first principals using geological maps and confirmed by field observation

➢ Interpretation can be derived from map patterns without stratigraphic columns

Parsons Range Group in upper part of rift phase thickens east into the faulted half-graben bounded on the east by the Bath Range fault
Practical application

➢ Use established criteria to assess basins
➢ All prospective basins must have all Essential criteria
➢ Basins can be ranked qualitatively or by numerical scores
➢ Identify key unknown criteria and acquire new data to resolve if possible
Proximity to large-scale basin-architecture fault corridor

➢ Large-scale (tens of kilometres) normal and transtensional strike-slip basin-architecture fault corridors
➢ Intra-basinal or basin-margin basin architecture faults

Modified from Mt Isa deep seismic transect; Gibson et al., 2016
Proximity to large-scale basin-architecture fault corridor

- Large-scale (tens of kilometres) normal and transtensional strike-slip basin-architecture fault corridors
- Intra-basinal or basin-margin basin architecture faults
- Lithostratigraphic or structural domain boundaries

Mueller, 2005
Accommodation and transfer zones along fault corridor

- Offset relays with splay zones, jogs on major fault zones in basin
- Transfer/transform fault zones.
- Defined by structural and stratigraphic data
- Interpreted dilational setting

Fossen and Rotevatn, 2016
Accommodation and transfer zones along fault corridor

Brooks Range; multiple Zn-Pb and Ba deposits within transfer zone in a fold and thrust belt reflecting primary basin-architecture faulting (from Young, 2004)

Belt-Purcell Basin, Hoy et al., 2000
**Play-scale Criteria**

**Palaeohighs**

- Fault-controlled basin/basement highs, intrabasinal or basin margin, especially horst or dome along major fault
- Thinned rift sequence, wedging out of clastic facies, coarse clastic aprons and debris flows
- Juxtaposition of basin and localised shallow-water facies
- Gravity and/or magnetic high
- Scale from 10-20 km to 1-2 km

Selwyn Basin, Goodfellow and Paradis
Sub-basins along fault corridor

- Defined by structure and stratigraphy
- Usually fault-controlled though this may not be manifest at the level of the host stratigraphy
- Thickened reduced units in sag phase
- May be a large basin with wacke fill and debris flows (e.g. McArthur River) or a more subtle, small scale and in some instances starved basin
- Quiet zones in magnetics and high conductivity EM signatures
- Sub-basins on large-scale palaeohigh

Howards Pass, Goodfellow and Jonasson 1986
Play-scale Criteria

HYC palaeohigh and sub-basins
HYC palaeohigh and sub-basins not defined on seismic line to north; observational scale and location, and inversion.
Meggen and Rammelsberg, palaeohigh and sub-basins along fault corridor; Large, 2000
Play-scale Criteria

Presence of reduced facies sediments

- Organic-rich **reduced** carbonaceous mudstone/siltstone facies intervals in sag (or rarely rift) stage within clastic-dominated sedimentary sequences
- **Dolomitic or ankeritic** reduced facies favourable
- Low sedimentation rate, starved basin intervals
- Pyritic facies
- **Conductive EM signature** and/or very quiet magnetic zones

From Goodfellow (unpublished) and Bacon groups after Rimmer (2004)

Howards Pass, Paradis and Goodfellow
Presence of reduced facies sediments

Brooks Range stratigraphy and deposits (from Kelley & Jennings, 2004)

Carbonaceous dolomitic shale; Sopokomil host sequence

Citronen Fjord, Kragh et al. 1997
Sullivan: hosted in interval dominated by grey argillite, siltstone, and calcareous micro-turbidite; Lydon, 2007
Mineralization and alteration

- **Zn-Pb-Ag ±Cu occurrences** in basin or platform facies (including vein), especially with structural focus along fault corridors

- **Conformable Pb isotope data**, including minor occurrences

- **Iron-carbonate alteration** in host sequence, footwall, or adjacent platform

- **Surface or lithogeochemical anomalism** in reduced sediments (above normal reduced host values), especially **Mn anomalism** in lithogeochemistry; **Alteration Indices**

- **Stratabound sedimentary barite** in reduced facies
Discovery of the Sopokomil SHMS Deposit in Sumatra, 1998

- Accidental discovery by gold-focused company (Herald Resources) which farmed into the property from PT Aneka Tambang
- Gold stream-sediment anomalism was not repeated, but strong Zn-Pb anomalism was defined
- Follow-up located outcropping massive sulphide mineralization in Lae Sopokomil creek

*What might have been*

- Sopokomil is right where you would expect it to be if exploring from first principals
- Can a first principal approach be applied successfully elsewhere, including in tectonically dismembered basins like Sumatera?
Neotethys Rifting

Tectonic Setting

- Rift and drift from Gondwana; Carboniferous to early Permian
- Dismembered rift-sag basinal sequences preserved through Sumatra and peninsular SE Asia
- Rift may not be preserved but can be inferred from tectonic setting
- No previous known occurrences of SHMS mineralization, but abundant reported Zn occurrences in Sumatra

300 Ma (Late Carboniferous) Stampfli and Borel, http://www.unil.ch/igp/page76652.html

Metcalfe http://metcalfeian.com/web-data/Research/PalGeog/Palaeogeog.html
➢ District-scale data identify basement high with anomalous geochemistry and wrapped by reducing sediments

Aeromagnetics – basement high and structural trend

Airborne EM – conductive sag-phase sediments

Stream sediment geochemistry, Zn anomalism over platform carbonates
Barisan Range, Sumatra

➢ Play-scale data outlined platform carbonates on paleohigh with Zn-Pb mineralization as main source of anomalous geochemistry

➢ EM defined dolomitic carbonaceous host-sequence, but not initially recognised as a potential SHMS target

➢ Potential only recognised when outcropping orebody discovered in Lae Sopokomil creek

Sopokomil Mineral Resource 24.3 Mt at 10.3% Zn, 6.0% Pb, and 8.3 g/t Ag (Measured, Indicated and Inferred)
Sopokomil Mineral Resource
24.3 Mt at 10.3% Zn, 6.0% Pb, and 8.3 g/t Ag
(Measured, Indicated and Inferred)
Sopokomil Trend

- Major structures controlling platform and basin facies distribution
- Successful discovery of multiple zones integrating lithofacies and structural understanding with airborne and ground EM, surface and lithogeochemistry

Airborne EM
Sopokomil Deposit

- Deposit-scale control of multiple lenses by syn-sedimentary faults and sub-basins
- Successfully targets using detailed structural interpretation from oriented core integrated with lithofacies analysis

Reynolds and Geerdts, 2010
Empirical approach integrated with mineral systems understanding

- A heuristic empirical approach can be very effective in identifying and ranking fertile basins for multiple deposit types, SHMS, Irish-type, MVT, VHMS, Sedimentary Cu, etc.
- Much can be achieved from first principals and limited follow up
- More challenging in heavily deformed or dismembered basins, but achievable
- Support by mineral system understanding, but not dependent on complex mineral system modelling
- Provides confidence to target basins without known deposits of the type target
- Confirm the system and use a similar approach to identify and prioritise plays
- Design programs to demonstrate play validity, not just to directly target mineralization
- Deposit-scale targeting integrates direct alteration or deposit signature criteria
- REMEMBER – every basin and deposit is different, despite shared characteristics
Thank You