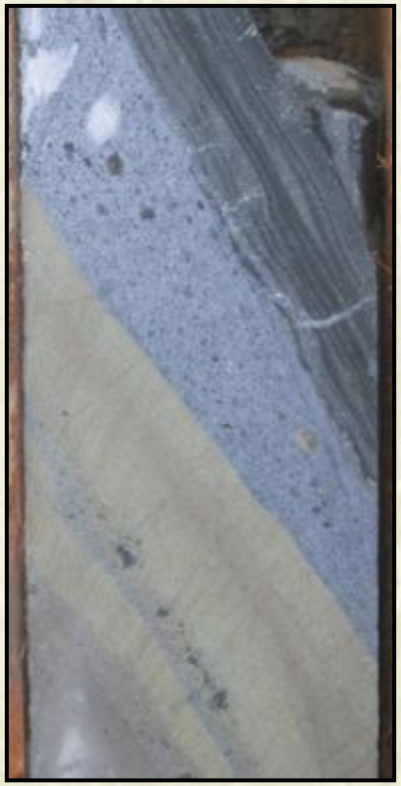
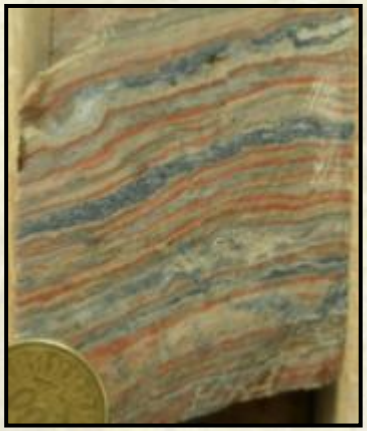
Diversity of Zinc-Lead Metallogeny

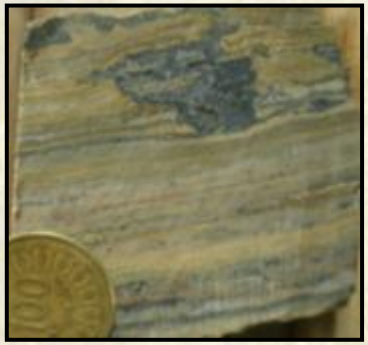
Implications for Targeting and Discovery

Neal Reynolds & Peter Muhling, CSA Global

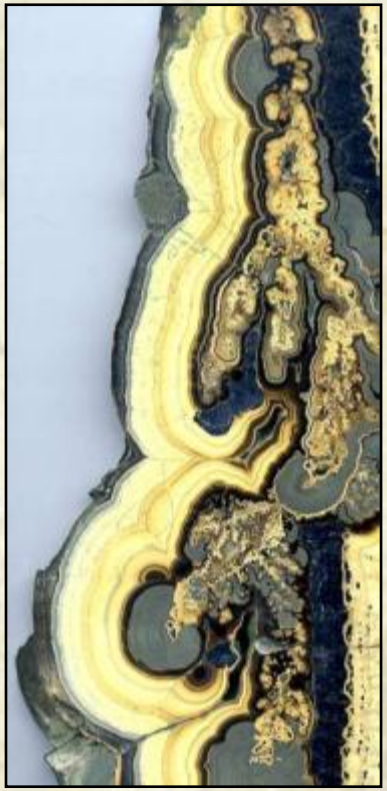


Sopokomil, Sumatra





Bou Aouane, Tunisia



Pomerazany, Silesia

Outline

- Zn-Pb deposit classification
- Economic importance
- Diversity of Zn-Pb metallogenic systems in the tectonic cycle
- Key Zn-Pb deposit styles
- Exploration & targeting models
- What are the optimum target styles?
- Where are the next discoveries?

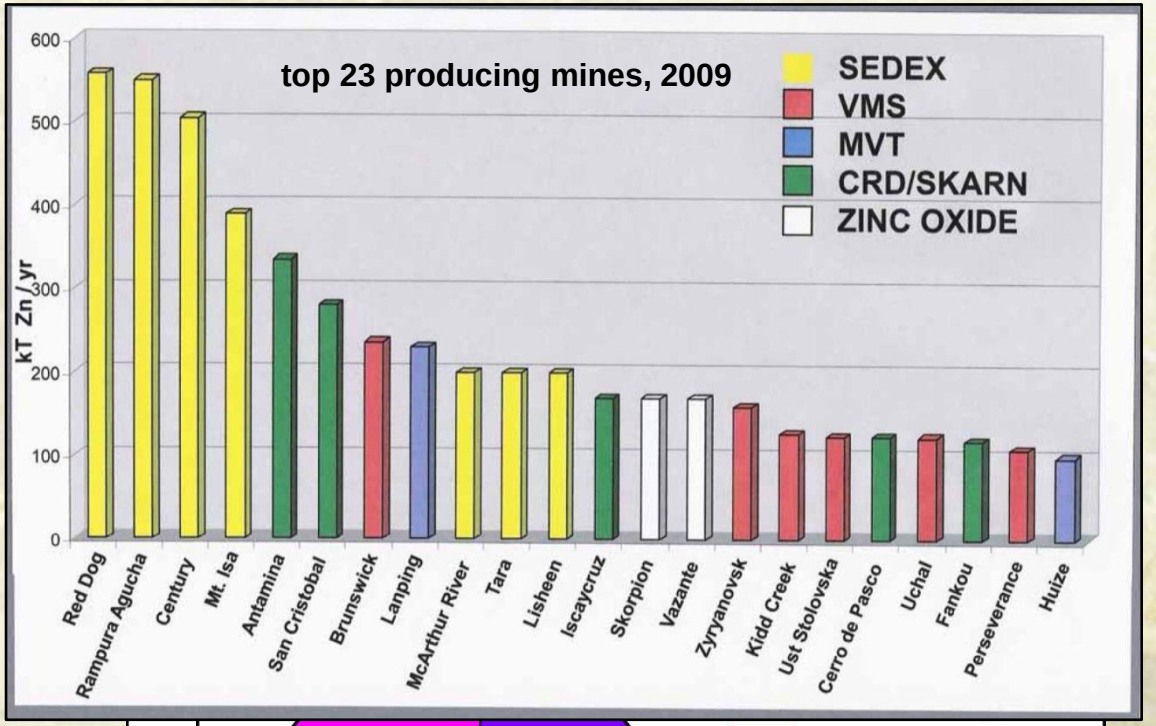
Zn-Pb Deposit Styles & Models – a Classification Nightmare!

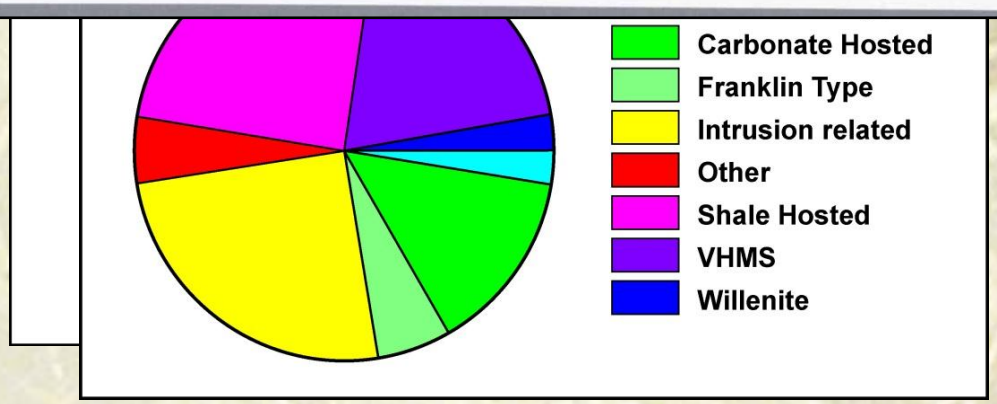
- Multiple overlapping terms and acronyms – VMS, VHMS, SHMS, Sedex, CD, BHT, Irish-type, MVT, CRD, Manto, Skarn, Diatreme/epithermal ……
- Different definitions by different workers.
- Confusion over individual deposits due to hybrid features and/or limited data
- Consider nine Zn-Pb deposit types, but recognise continuums and hybrids:
  - *VHMS (volcanic-hosted massive sulphide or VMS)*
  - *SHMS (shale-hosted massive sulphide or "Sedex"*
  - *BHT (Broken Hill-type)*
  - *Irish-type*
  - *MVT (Mississippi Valley-type)*
  - *Zn-silicate (hypogene non-sulphide Zn – willemite and franklinite types)*
  - *Manto (or CRD, carbonate-replacement deposit)*
  - *Skarn*
  - *Diatreme & Epithermal.*
- Supergene oxide deposits represent a distinct target type, but not a genetic style.
- *Origin of some large deposits is still disputed, and many are transitional "hybrids".*

Zn-Pb Style, Endowment & Economics

- SHMS dominates resources
- Confused by different "pigeonholing" – "Sedex" here includes Irish-type and BHT – and ignores hybrid types
- Significant production from VHMS, MVT/Irish, and Skarn/Manto – declining in importance?
- Significant production from "oxide"
- SHMS dominates the major producing deposits

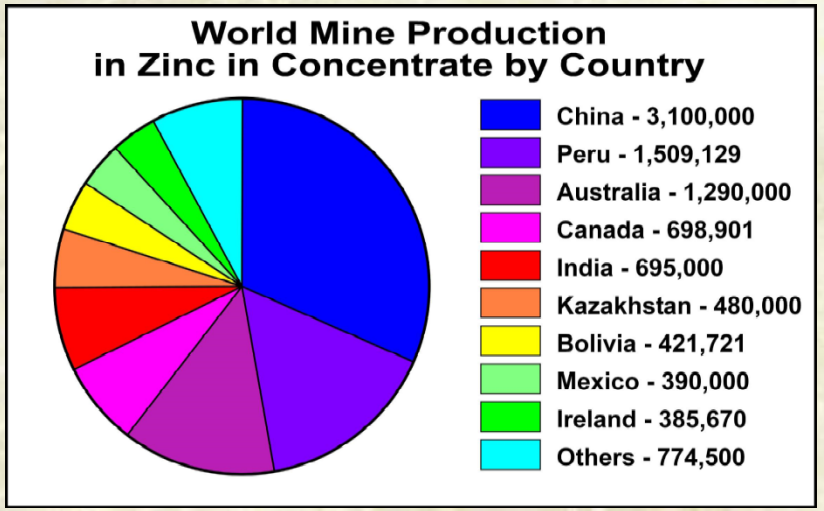
- *but where are the new SHMS discoveries?*

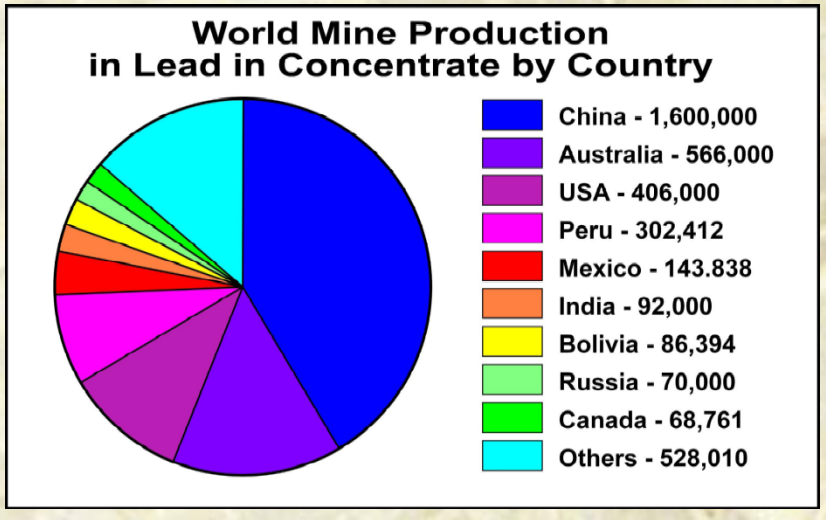




Zn-Pb Production & Outlook

- Annual mine production
  - 11.2 Mt Zn (c. 70% of total)
  - 4 Mt Pb (c. 45% of total)
- Zn – top 5 produce 70%
- Pb – top 5 produce 78%
- Production very fragmented, especially in China & Latin America
- Four largest Zn producers (Vedanta, Xstrata, MMG and Teck) only produce about 25% of global production
- China has been a critical player, until 1990s as an exporter, now as the biggest producer, but also an importer.

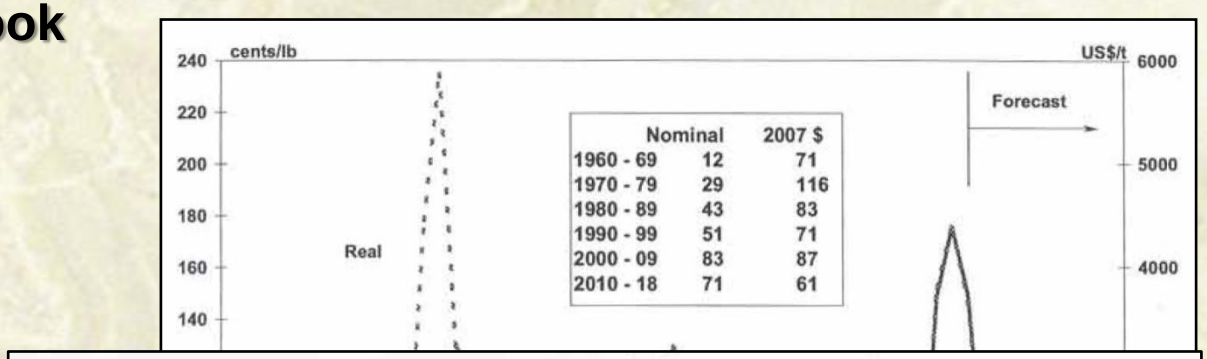


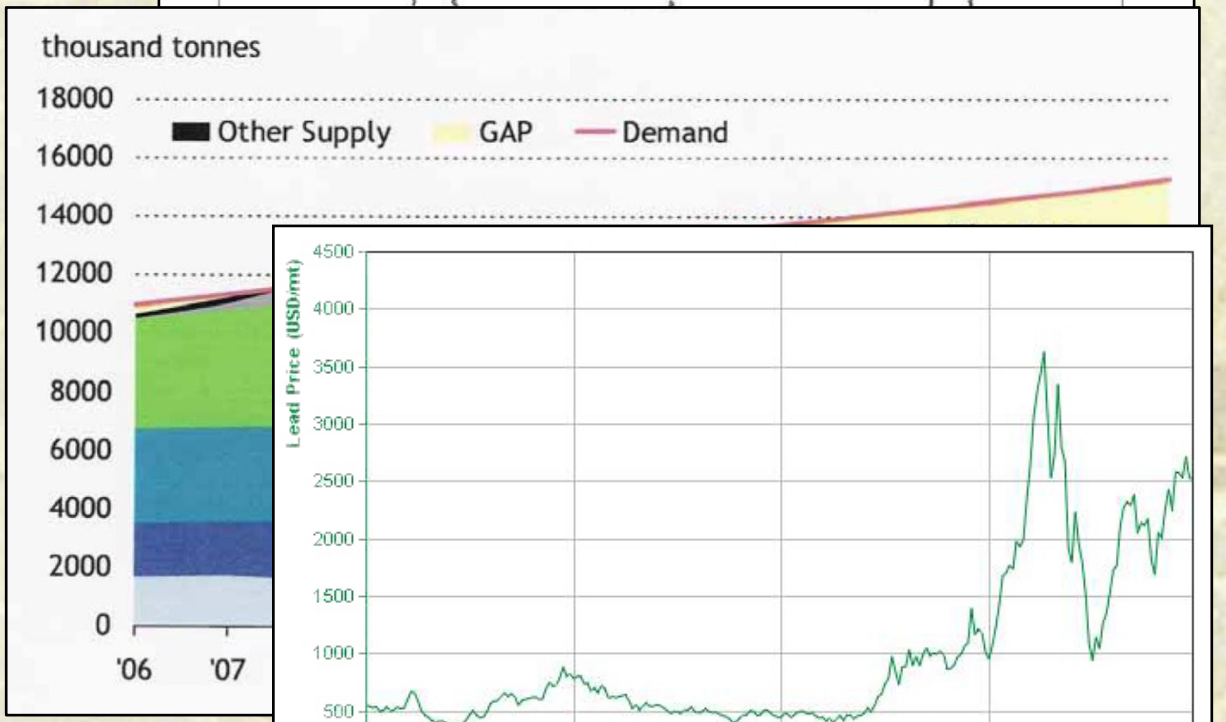


2009 figures from USGS

Zn-Pb Production & Outlook

- Highly cyclic market, much production only profitable in upswings
- Secular change underway? Opening “Zn Gap” as old mines close in the next 5 years and few new projects.
- Rebound of Pb demand and price despite recycling – driven by battery demands of “renewable” energy
- New production almost all from known deposit development, expansion, or peripheral discovery



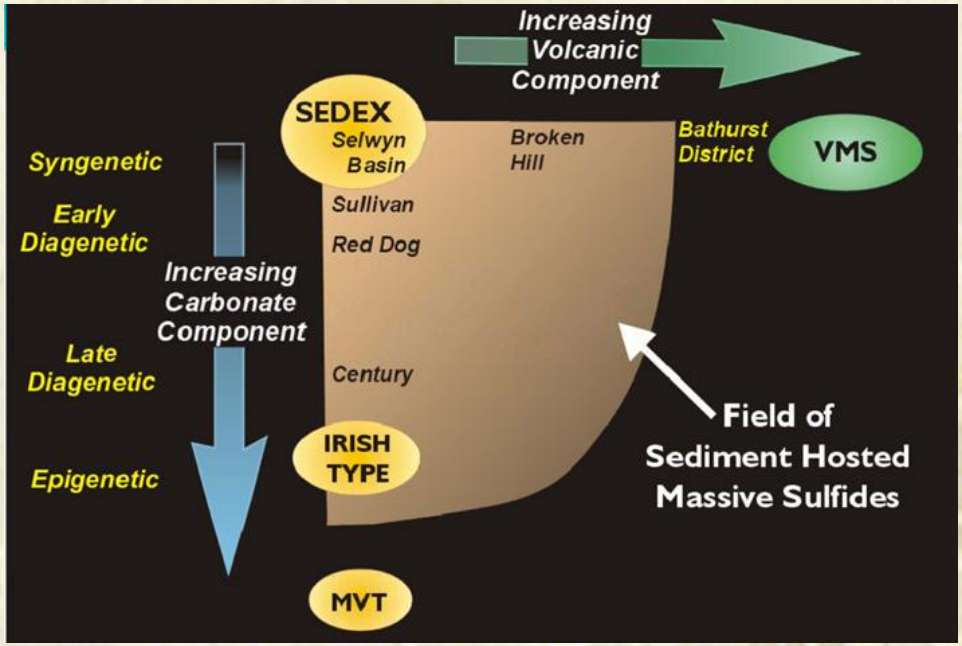


from Brook Hunt

Diversity of Economic Zn-Pb Deposit Styles

Broadly group:

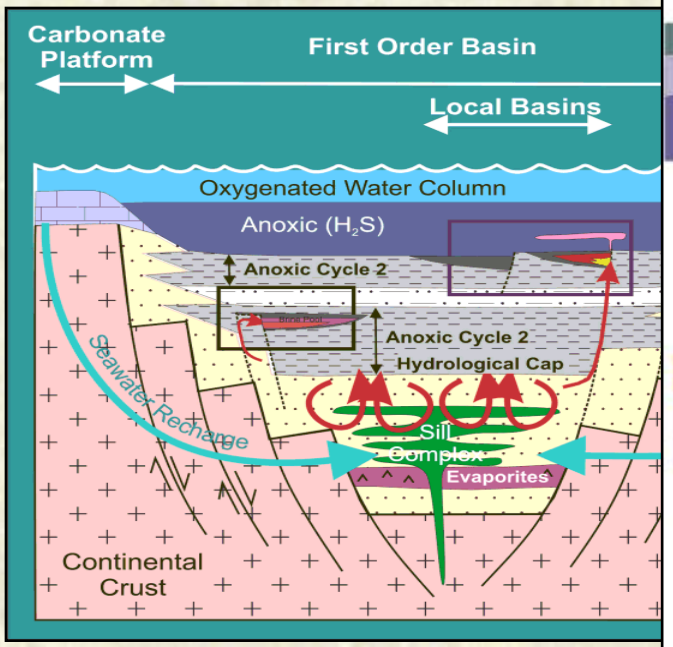
- "Magmatic arc deposits" formed by fluid systems driven by intrusion, typically sub-volcanic porphyries – manto/skarn, diatreme & epithermal.
- "Basinal deposits" formed by large- or regional-scale fluid-flow systems in basin settings – VHMS, SHMS, BHT, Irish-type, MVT
  - *VHMS deposits formed in volcano-sedimentary basin settings and show transitional relationships to SHMS but differ from other basinal deposits in being directly driven by magmatic heat*
  - *Basinal deposits include deposits formed during basin extension, inversion, and compression.*
  - *More complex fluid systems than those related to magmatism*



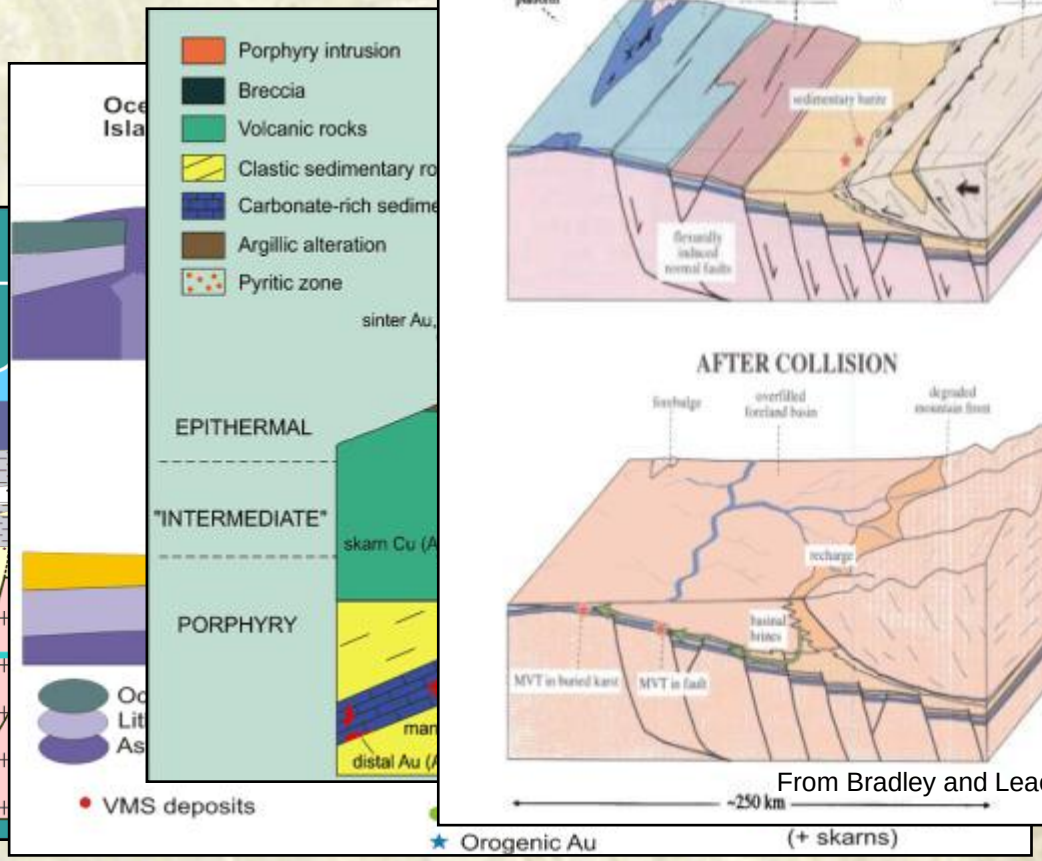
from Allen, 2003

Zn-Pb in the Tectonic Cycle

- **Rift/Sag/Inversion –** *SHMS, Irish-type, (MVT)*; *VHMS*
- **Convergence –** *VHMS, skarn/manto (CRD), epithermal*
- **Collision & Collapse –** *MVT, "Hybrid"*



From Goodfellow, 2007

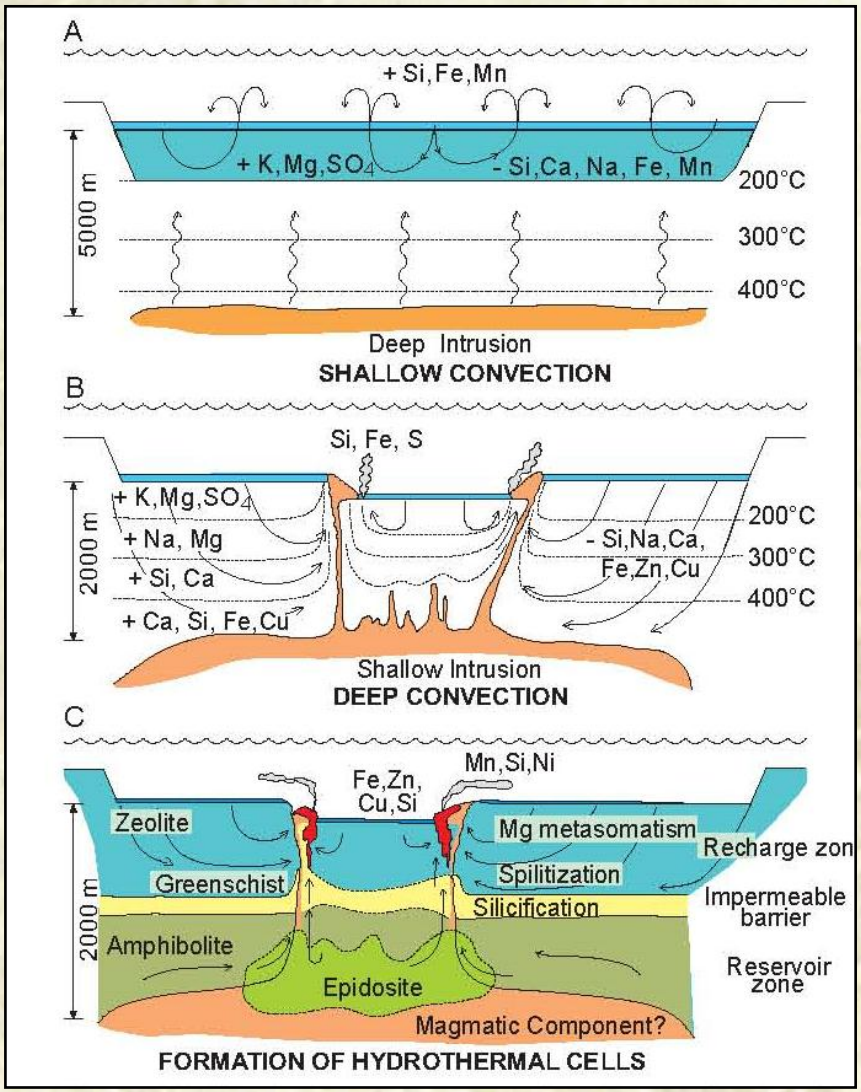


From Galley et al, http://cgc.rncan.gc.ca/mindep/synth_dep/vms/index_e.php

From Bradley and Leach, 2002

VHMS – Key Features & Model

- Broadly strata-bound, massive to semi-massive sulphides ± footwall stockwork, commonly fault-controlled.
- Extensional setting, commonly back-arc.
- Submarine volcanics, typically deep water, ± intravolcanic sediments; 'fertile' footwall intrusions.
- Zoned alteration.
- Range from Cu-rich to Zn-Pb-rich with or without high Ag or Au, related to magmatic chemistry and influence of sediments.
- Golden Grove, Teutonic Bore/Jaguar, Sulphur Springs, Whim Creek, Rosebery, Hellyer, Woodlawn, Benambra, Lewis Ponds, Thalanga
- Metals leached from the volcanic ±sediment pile in convection systems driven by magmatic heat.
- Sea-floor or sub sea-floor metal deposition
- Structural fluid focus, trap sites related to sea-water mixing, cooling, and host-rock reaction.



from Galley et al., 2007

VHMS – Economic Factors

- Includes some huge deposits and significant districts (e.g. Neves Corvo c. 270Mt, 9Mt contained metal; Brunswick No 12, 230Mt at 0.5% Cu, 7.7%Zn, 3% Pb, 91g/t Ag, 0.5g/t Au)
- Most individual deposits are small but may be many deposits in a single district (e.g. Noranda)
- Variable grade, but typically polymetallic and may have significant precious-metal credits
- Metallurgy may be complex, but ore may be high value (Eskay Creek 4Mt at 0.33% Cu, 5.4% Zn, 2.2% Pb, 998g/t Ag and 26.4g/t Au)
- Discrete massive bodies, straightforward mining.
- Effective exploration model and methodologies
  - volcanic lithostratigraphy & structure,
  - alteration vectoring
  - geophysics – EM
- *But there is significant variability & exploration challenges in deeply weathered terrain*

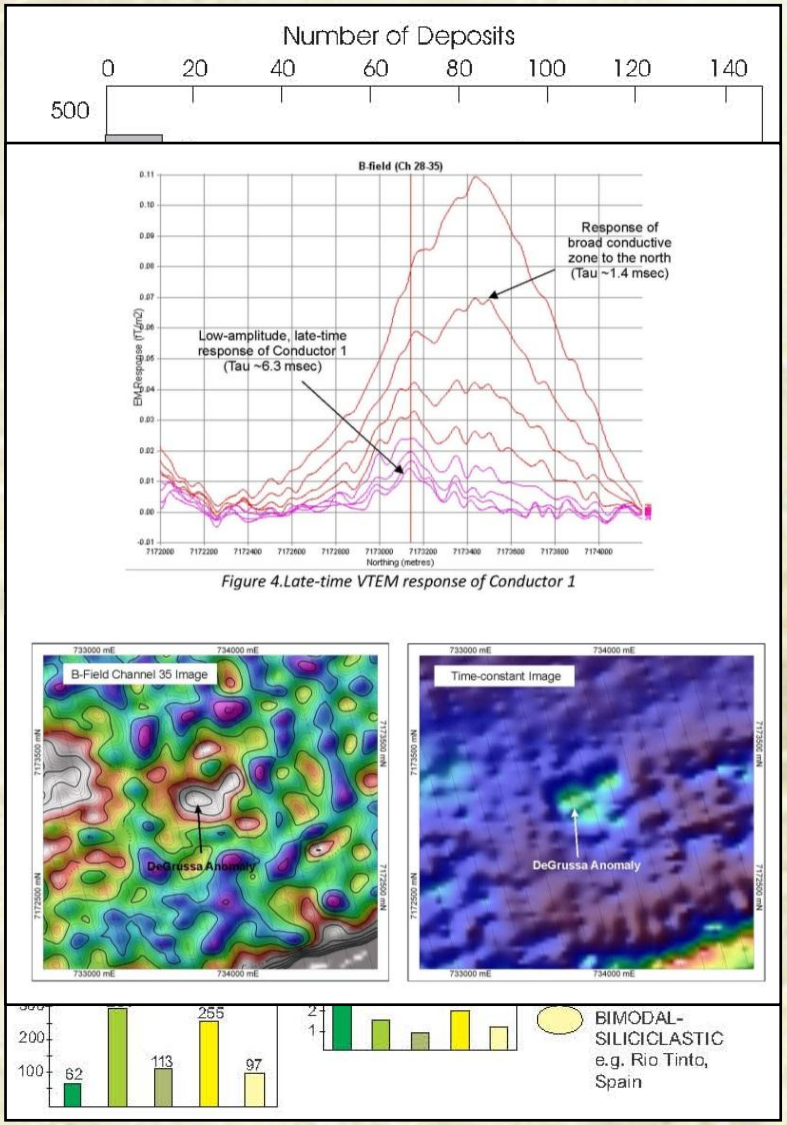
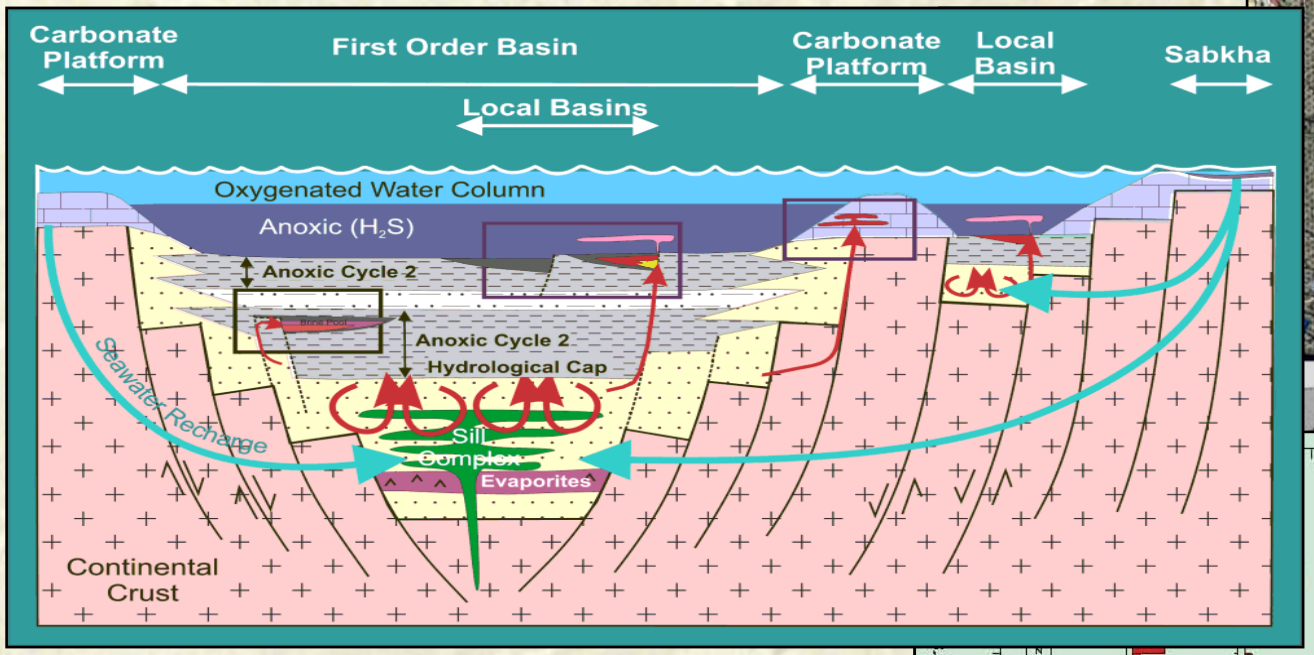


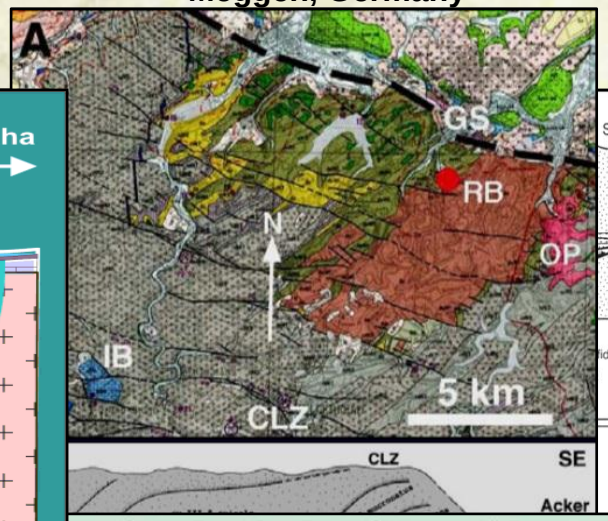
Figure 4.Late-time VTEM response of Conductor 1

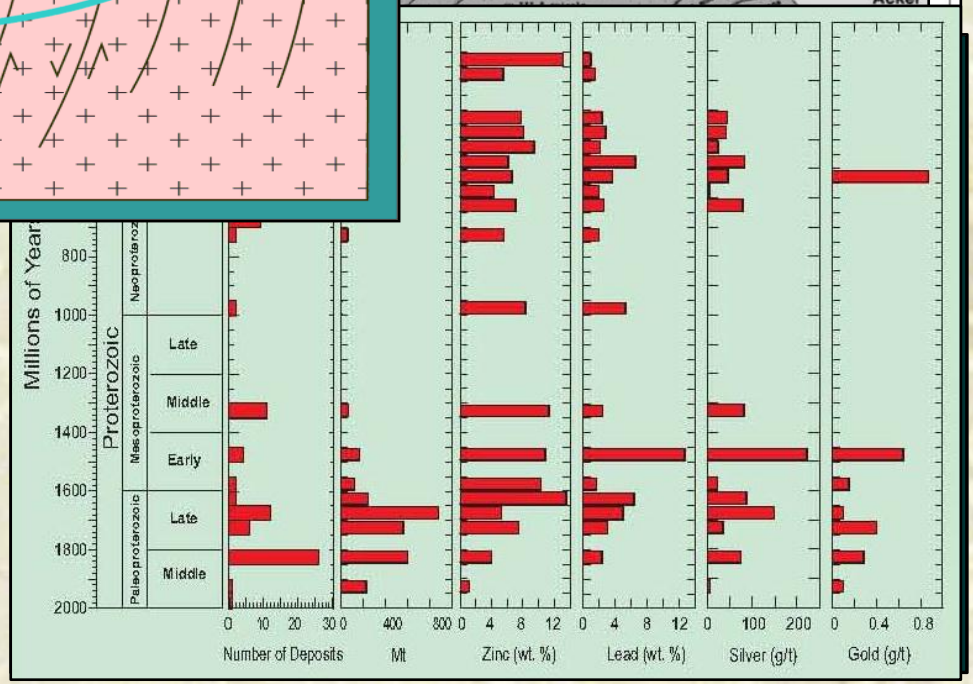
from Galley et al., 2007

SHMS – Key Features & Model



Meggen, Germany



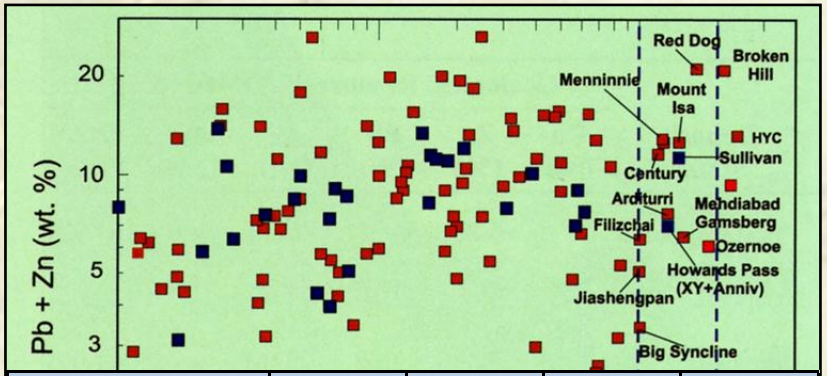


- Metals leached by large long-lived basin-scale metal-leaching convection systems.
- Expulsion linked to tectonic events
- Sea-floor to late diagenetic metal deposition.
- Structurally focused fluid focus; trap sites include anoxic sub-basins, favourable reactive reduced carbonate host-rocks, possibly hydrocarbon reservoirs.

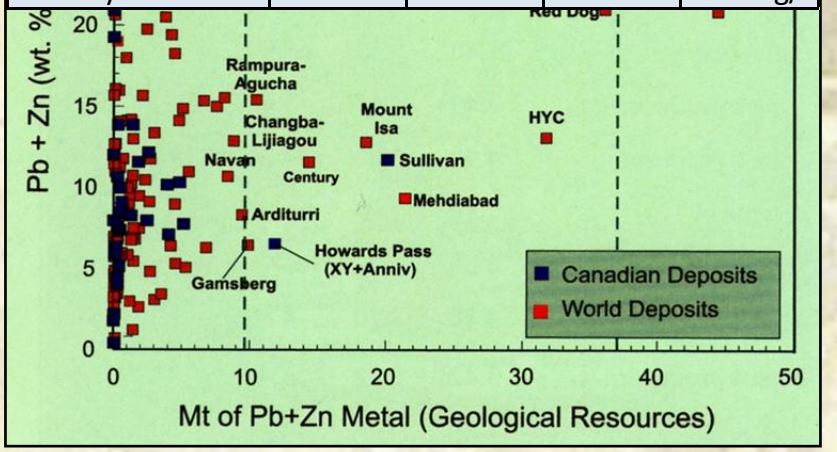
From Goodfellow & Lydon, 2007

SHMS – Economic Factors

- Biggest Zn-Pb deposits and greatest metal endowment; moderate to high grades;
- Metallurgy variable, can be problematic (e.g. HYC) or attractive if recrystallised (e.g. Rampura Agucha)
- Long-life projects, large-scale mining
- Few discoveries under cover – challenging exploration
  - Fertile basins and ages
  - Geological targeting – "play-scale" approach; basin analysis, fluid modelling
  - Geophysics, (litho)geochemical haloes, alteration vectoring, cryptic alteration, isotopes
- McArthur River, Mt Isa, Century
- Red Dog, Howards Pass, Sullivan, Sopokomil, Ozernoye, Kholodninskoye, Rampura Agucha, Changba-Liajiagou, Meggen, Rammelsberg, Huogeqi, Dongshengmiao



Deposit	Tonnage	Zn %	Pb %	Ag g/t
McArthur River	227	9%	4%	60g/t
Red Dog	165	17%	5%	
Sullivan	162	5.9%	6.10%	67g/t
Mt Isa	150	7%	6%	150g/t
Changba-Liajiagou	143	7%	1%	
George Fisher	107	11%	5%	93g/t
Rampura Agucha	107	12%	2%	50g/t
Century	95	13%	2%	46g/t



From Goodfellow & Lydon, 2007

BHT – Key Features, Model, & Economic Factors

- Stratabound sulphide-rich Pb-Zn-Ag deposits, may have elevated Au and other trace elements.
- High-grade metamorphosed Palaeoproterozoic continental rift sequences with volcanics and shallow intrusives.
- Large metal-leaching convection systems in high-heat flow rifts.
- Sea-floor to diagenetic metal deposition from fault controlled brines.
- Substantial retrograde metasomatism – metamorphic/metasomatic models also postulated.

From Goodfellow & Lydon, 2007

- Large or giant deposits, but rare.
- Attractive grades, Ag credits.
- Metallurgy can be problematic (e.g. Gamsberg).

- Broken Hill, Cannington, Gamsberg
- Sullivan – hybrid?
- *Distinguish from metamorphosed SHMS/VHMS (e.g. Zinkruvan)*

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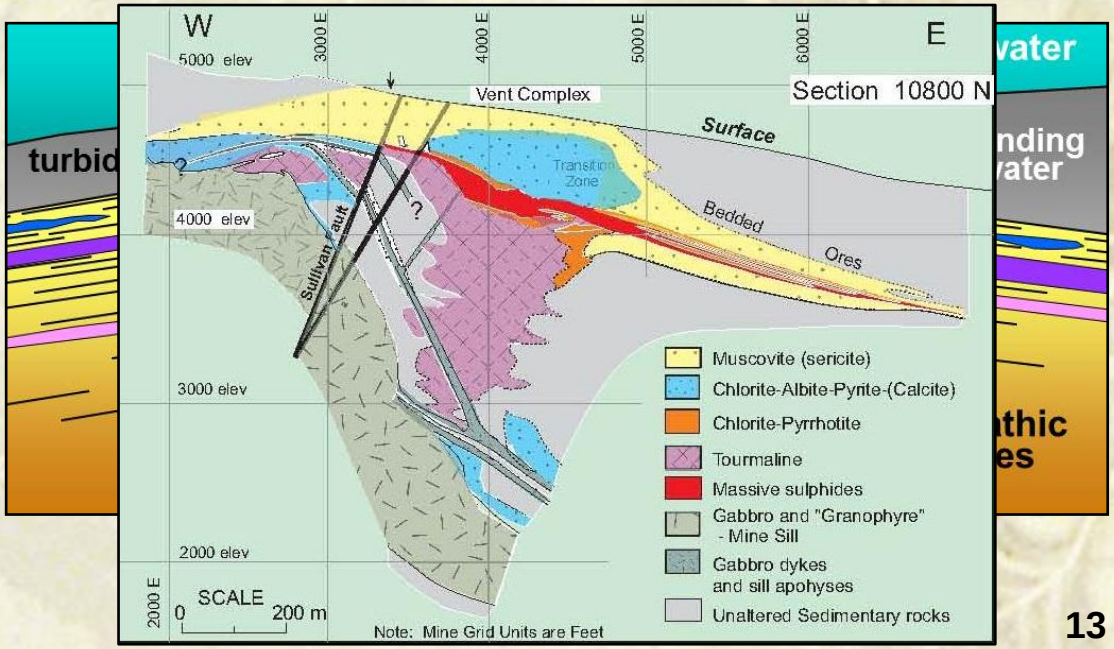
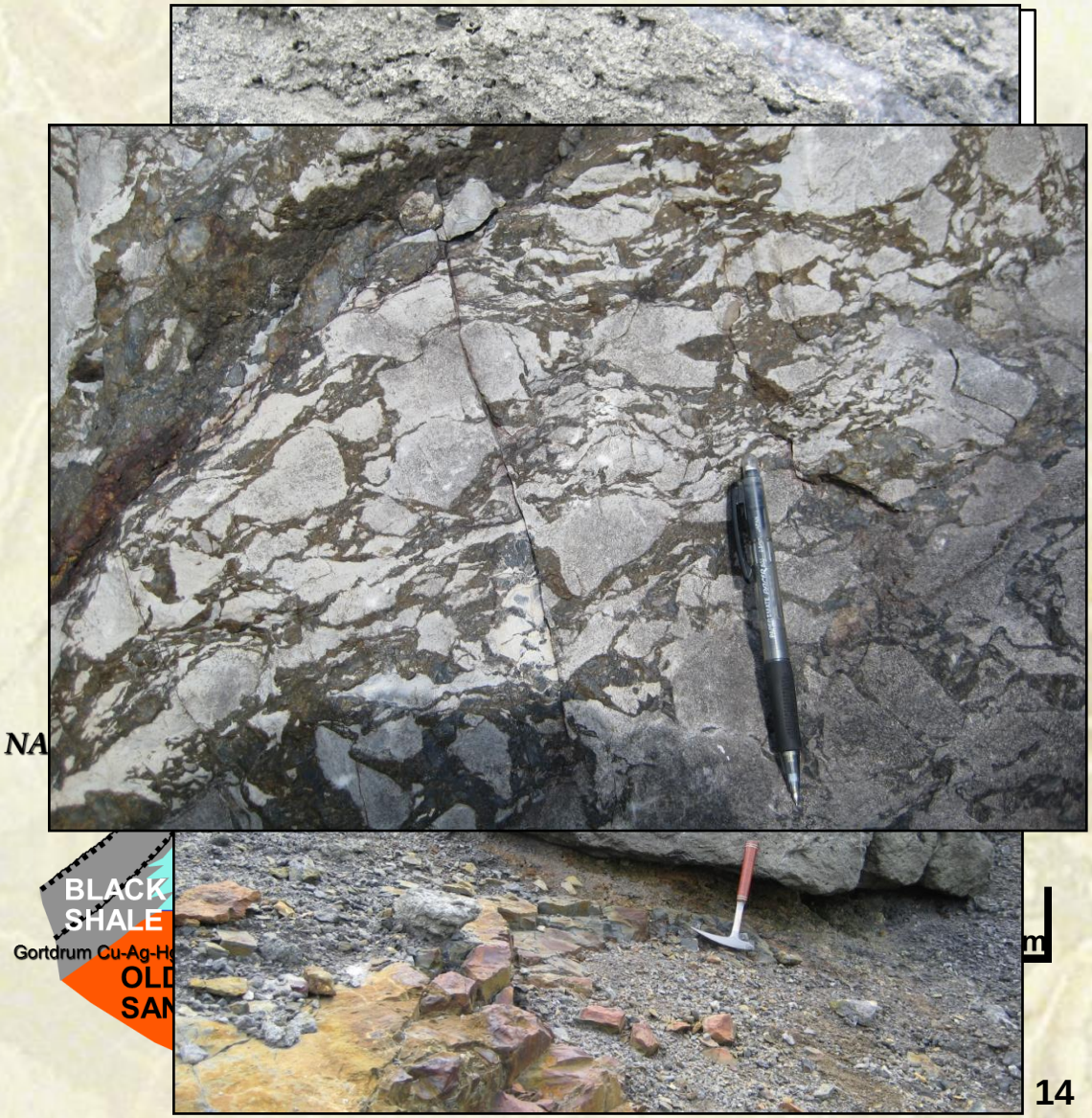


Irish-type – Key Features & Model

- Stratabound or stratiform, fault-controlled, moderately sulphide-rich Zn-Pb-(Ag) deposits.
- Open-space fill & replacement; 1st favourable carbonate horizon
- Platform to basinal carbonates peripheral to rift-sag basins.
- Volcanics – high heat flow

- Metals leached from basinal sediments and basement
- Tectonic-driven fluid expulsion – basin extension & inversion events
- Late-diagenetic mineralisation.
- Structural fluid focus, trap-sites controlled by reactive carbonates, dolomite aquifers, aquicludes, and fluid mixing.

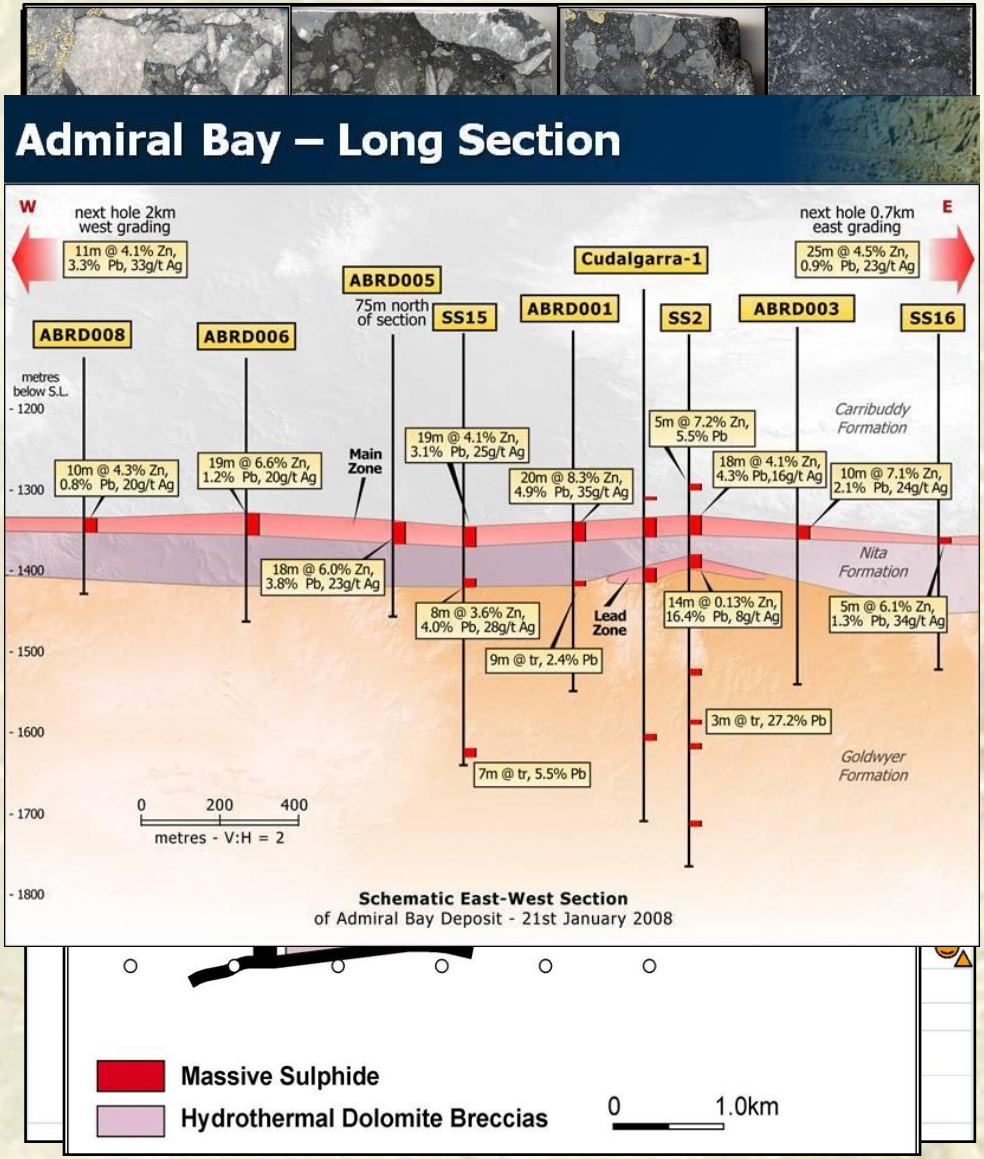
Silvermines, Tipperary



Irish-type – Economic Factors

- Small to very large and economically attractive deposits
- Irish Midlands Orefield >170 Mt at grades of ~12% Zn+Pb; new Pallas Green discovery >25Mt and open
- Rare or common? Prevalence depends on classifiers bias!
- Favourable metallurgy
- Successful blind discoveries
  - Geological and alteration targeting, basin analysis, fluid modelling
  - Geophysics – IP and EM
- Admiral Bay, Warrabarty, Dome 5? (3m @ 11.8% Zn, 4.0% Pb, 63g/t Ag)
- Navan, Lisheen, Pallas Green, Silvermines
- Morro Agudo, Duddar, Mehdi Abad (c. 394 Mt at 4.2% Zn, 1.6% Pb, and 36g/t Ag); Bleiberg; Bo Yai; Bawsaing

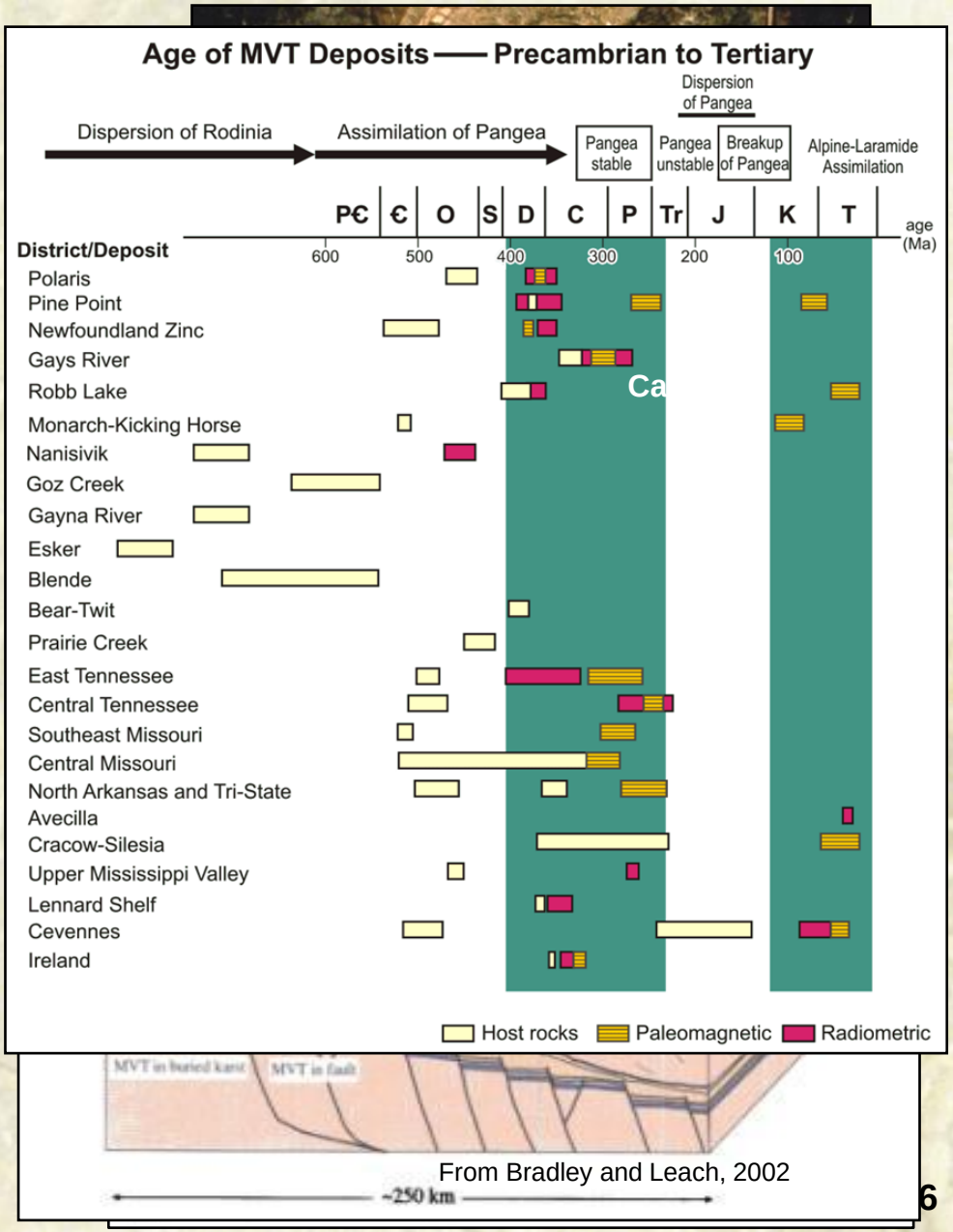
Lisheen, Tipperary



MVT – Key Features & Model

- Stratabound and cross-cutting, low-T cavity-fill deposits, often very irregular karst-fill.
- Relatively sulphide-poor; Zn-Pb, may have barite, rarely Cu.
- Platform carbonates peripheral to rift-sag basins, typically passive margins affected by collisional orogens.

- Late- to very late-diagenetic metal deposition from basinal brines expelled by tectonism and/or hydraulic head due to orogenic uplift.
- *or fluid systems driven by extension & inversion prior to orogenic collision.*
- Aquifer fluid focus, trapping related to pinch-outs, aquicludes, fluid mixing, often localised within pre-existing meteoric karst.



From Bradley and Leach, 2002

MVT – Economic Factors

- Includes some of the largest Zn-Pb districts (e.g. Silesia c. 700 Mt at 4.2% Zn, 1.3% Pb).
- Typically low grade.
- Excellent metallurgy and high-grade concentrates.
- Often irregular and complex to explore and mine.

- Lennard Shelf (41Mt at 7.9% Zn, 3.1% Pb); Wonawinta
- Reocín, Polaris, Nanisivik, Pine Point, Gays River, East Tennessee, Viburnum Trend, Daliangzi, Bou Beker

TOTAL IN SITU LENNARD SHELF RESOURCES AS AT 30 JUNE 2003

Total In Situ Resources refers to the Total Resource Tonnage present before Mining.

DEPOSIT	CUTOFF GRADE	TONNES	Zn %	Pb %	Ag g/t
Cadjebut	6% Zn Eq	5,215,000	11.20	3.20	
Cadjebut Splay Fault	5% Zn Eq	390,000	1.40	14.40	
Goongewa	Various	2,571,000	8.50	2.80	38
Kapok/Kapok East	5% Zn Eq	3,373,000	9.30	8.18	
Kapok West	5% Zn Eq	1,220,000	4.30	9.00	
Kutarta	5% Zn Eq	2,340,000	7.20	0.50	39
CADJEBUT TREND		**15,109,000**	**8.89**	**4.58**	
Pillara	3% Zn Eq	23,194,000	7.12	2.20	
Napier Range	5% Zn Eq	590,000	8.50	8.00	75
Fossil Downs	3% Zn Eq	2,150,000	9.45	2.07	50
TOTAL		**41,043,000**	**7.91**	**3.15**	

District	Subdistrict – Deposit	Area km2	Tonnage Mt	Zn%	Pb%	Contained Metal Mt
SE Missouri	Total	2500	c. 800	0.5	4.5	c.35
SE Missouri	Viburnum	500	420	1	6	29.4
SE Missouri	Old Lead Belt	1500	370		3	11.1
Silesia		c. 3200	>500	4-5	1-2	39
Central Tennessee		c. 5000	c. 500	3	0.1	15.5
East Tennessee		c. 7500	c. 500	3		15
Tri-State		c. 1800	c. 500	2.3	0.6	14.5
Pine Point		1600	94.5	6.2	2.5	8.2
Illinios-Wisconsin		?	100	5	0.5	5.5
Cornwallis	Polaris	?	24.1	13.8	4.2	4.3
Lennard Shelf		6500	35.3	8.9	3.8	4.5
U. Mississippi Valley		7800	44	2.7	1.8	2.0

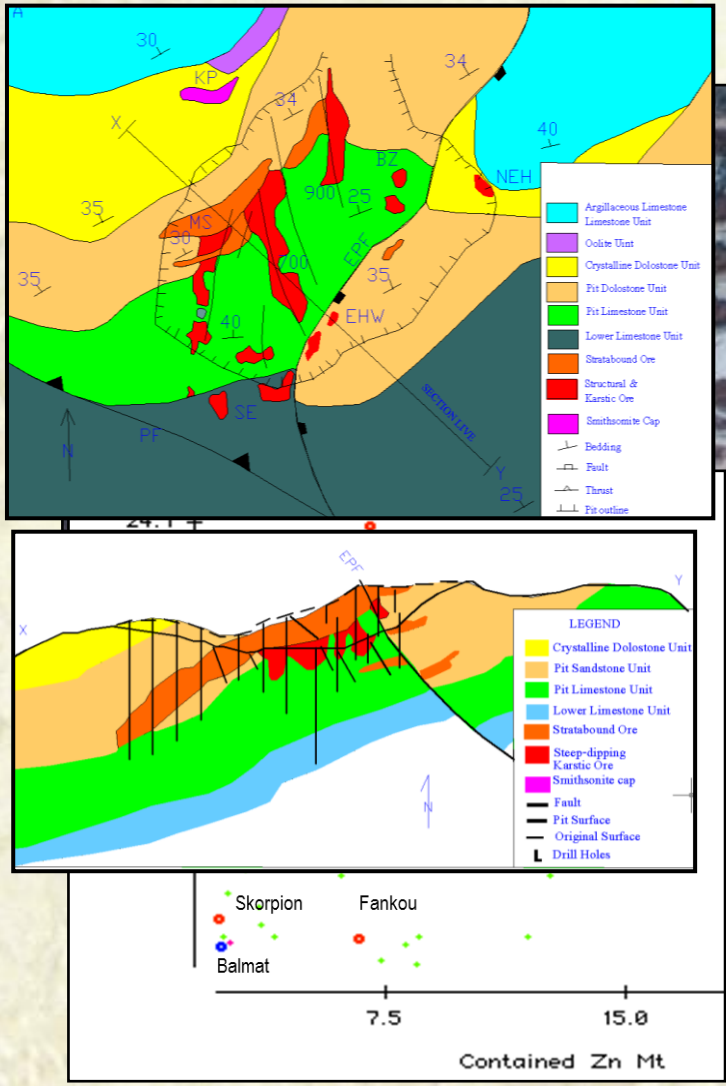
"Zinc-silicate" or "Hypogene Non-sulphide Zinc"

- "Willemite-type" – stratabound and structurally controlled replacement and open-space fill within Neoproterozoic platform carbonates (Beltana, Aroona, Vazante, Kabwe)
- "Franklin-type" – stratabound within high-grade metamorphic carbonates (Franklin Furnace, 21.8Mt at 19.8% Zn)
- Typically very high grade, may be large (Vazante c. 20Mt at 23% Zn)
- Amenable to leaching and Zn-metal production.
- May have irregular and complex geometry.

Supergene Non-Sulphide Zinc

- Mostly small but some large and high-grade (e.g. Jinding, c. 200 Mt at 6.1% Zn, 1.3% Pb; Angouran, 14.6 Mt at 22% Zn and 4.6% Pb)
- Typically carbonate-hosted (MVT or manto) precursor, but may be other styles (e.g. Skorpion – VHMS)
- Hemimorphite amenable to leaching, smithsonite may have high acid consumption (ammonia leach option)

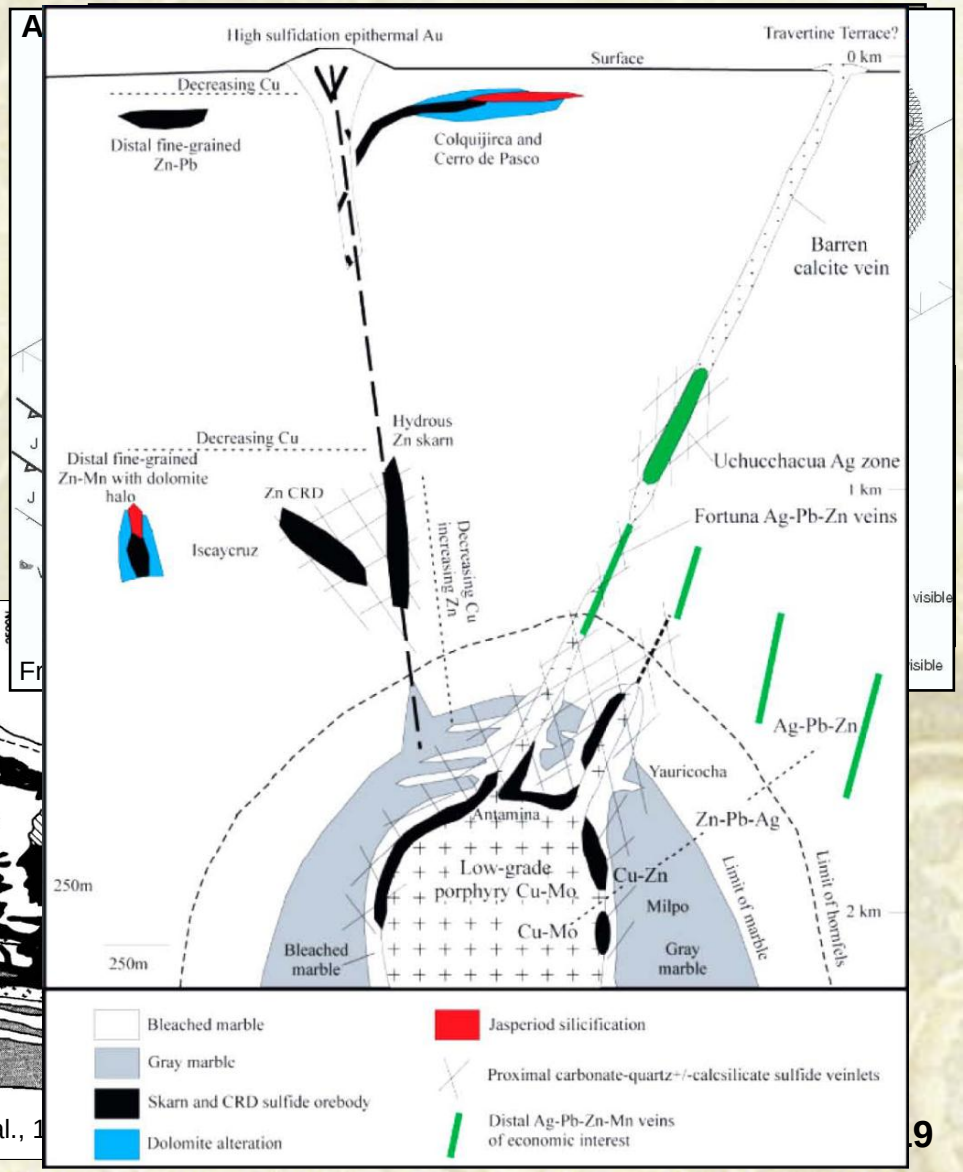
Padaeng, Thailand

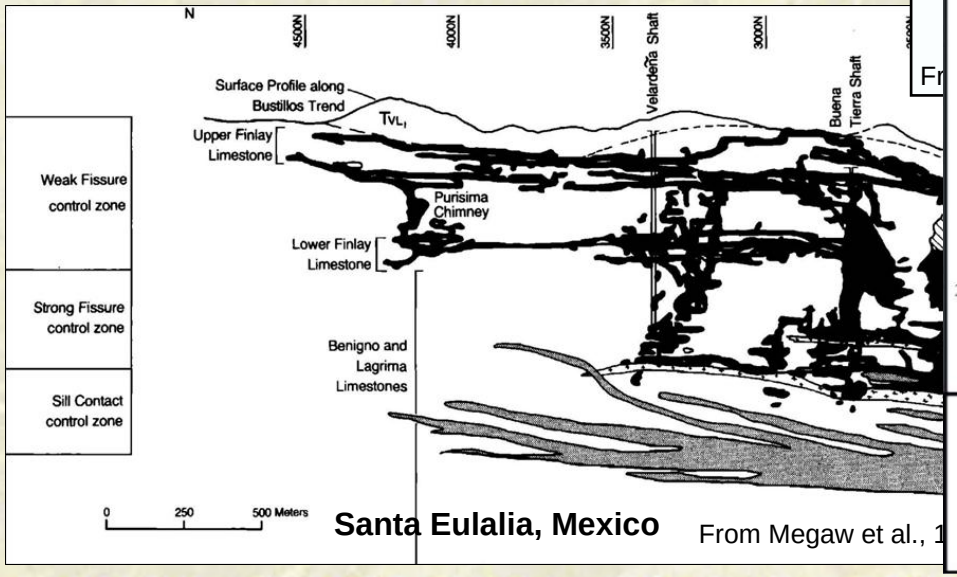


Manto/CRD, Skarn – Key Features & Model

From UBC

- Stratabound, structurally and/or karst-control, may be distal from intrusion.
- Coarse, sulphide-rich replacement, quartz-carbonate gangue.
- Polymetallic with Ag, Au, high-Fe, Mn.
- (Young) platform carbonates in arc settings.
- Skarn – Ca/Mg-silicate gangue; normally proximal to a sub-volcanic intrusion, may be contact-controlled.





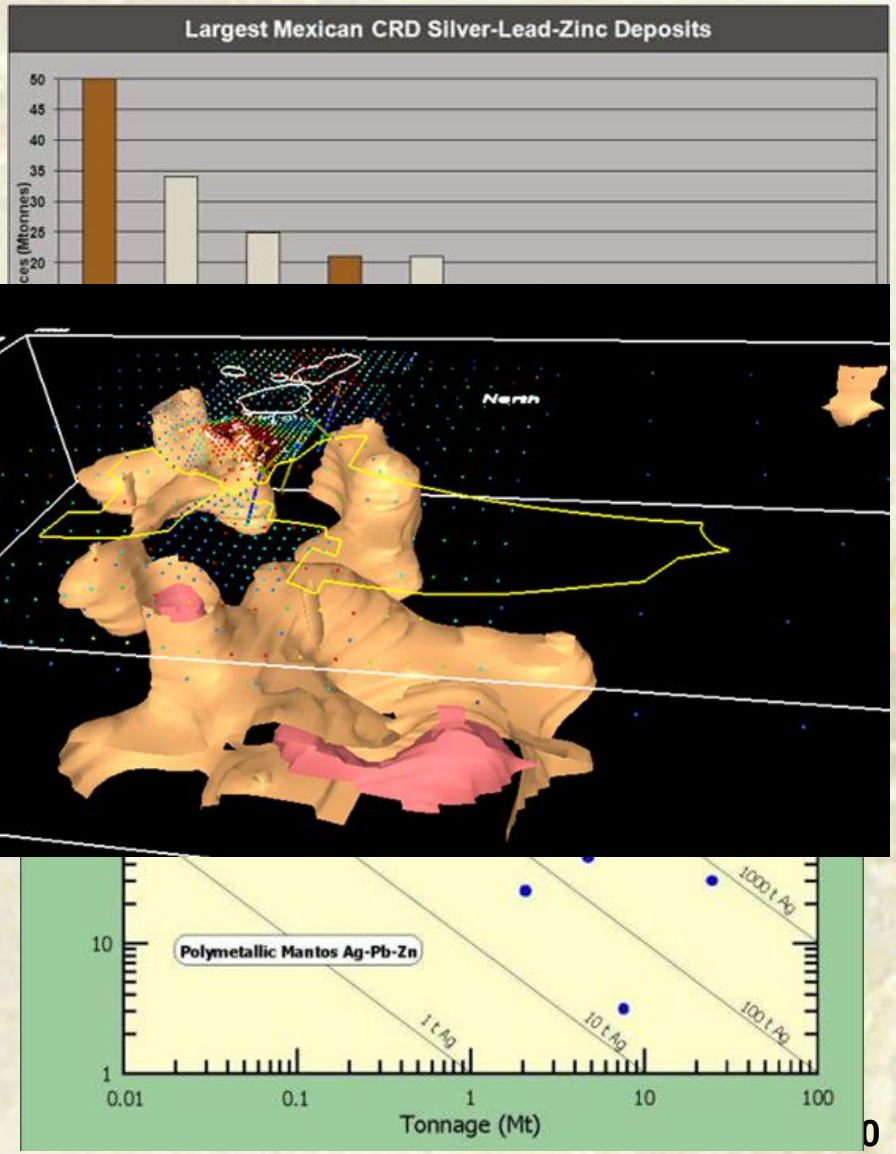
Santa Eulalia, Mexico

From Megaw et al., 1

Manto/CRD & Skarn – Economic Factors

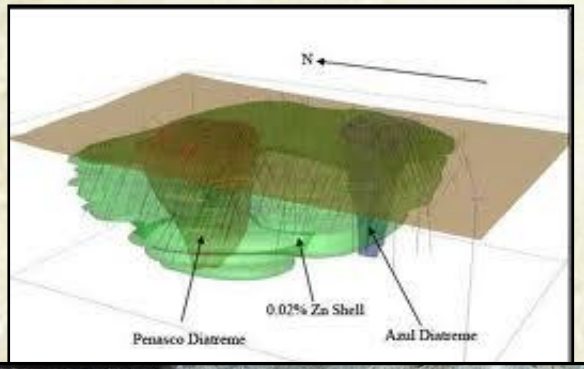
- Large global endowment largely reflects Latin American Cordillera of Peru & Mexico, including giant deposits (e.g. Antamina – 23Mt Zn, Santa Eulalia) & SE China (e.g. Fankou, Shuikoushan)
- Often high grade and may have significant precious-metal credits or be polymetallic – Zn-Pb-Ag-(Au), Zn-Cu-Mo-Bi (1.5Bt @ 0.93% Cu, 0.51% Zn, 10.9g/t Ag, 0.02% Mo), Zn-Sn-Ag (e.g Dachang c. 144 Mt @ 0.7% Sn, 2.4% Zn, 0.3% Pb, >100 g/t Ag)
- Metallurgy may be complex, but ameliorated by value
- May have irregular and complex geometry
- Geophysics can be effective – 3D IP

- Mt Garnet, Zeehan, Menninnie Dam?
- Leadville, Trepča, Cerro de Pasco, Iscaycruz, Mochito, Toqui



Diatreme & Epithermal

- Breccia-hosted & sheeted vein systems within volcanics associated with porphyritic stocks and dyke complexes.
- Intermediate sulphidation; can occur in porphyry districts.
- Typically small deposits, though some large low-grade polymetallic deposits.
- Economics depend on precious metal content.
- Significant deposits include recent discoveries -
  - Peñasquito diatreme breccia (Mexico) – 1.4Bt @ 0.4g/t Au, 23g/t Ag, 0.57% Zn, 0.39% Cu, 0.25% Pb
  - San Cristobal vein and breccia (Bolivia) – 240 Mt @ 64g/t Ag, 1.67% Zn 0.58 %Pb),
  - Yinshan (Lower Yangtze porphyry district) – 157 Mt @ 2.3% Zn, 1.4% Pb, 0.55% Cu, 0.7 g/t Au, and 8g/t Ag
  - Shahumyan (Armenia) – 12.4 Mt @ 2.5% Zn, 0.56% Cu, 0.2% Pb, 2.5 g/t Au and 50 g/t Ag
- Overlooked as a Zn target – Peñasquito 8.1Mt contained Zn.



Zn-Pb Discovery

- Dearth of new greenfields discoveries in last 15 years.
- Bentley (2008), Jaguar (2002), Century, Cannington, Sulphur Springs (1990).
- Stonepark (2009), Reed Bay, Lalor (2007), Penasquito, Pallas Green (2003), Sopokomil (1998), San Nicolas (1996), Citronen Fjord (1993), Lisheen (1990).

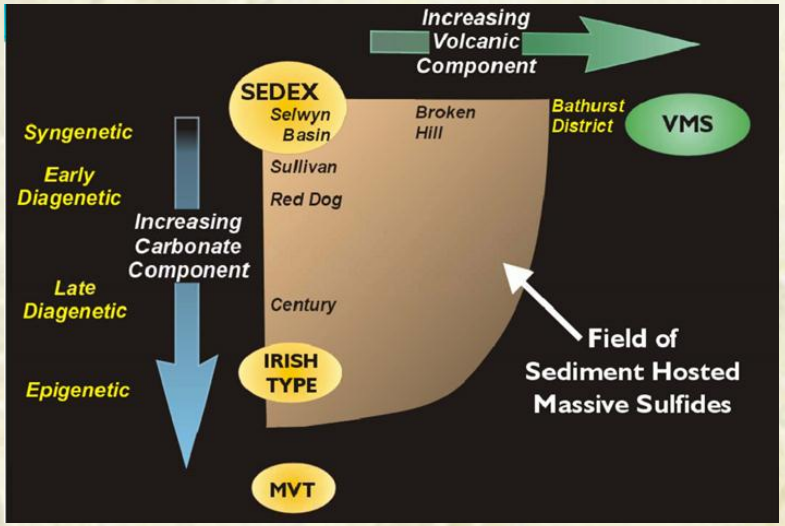
- ***Where will new discoveries come from? Style and location?***
- ***What are the most attractive target styles?***
- ***Potential of "non-conventional" styles?***
- ***Where do we start – old districts or new?***

Pallas Green, Limerick

Citronen Fjord, N Greenland

Zn-Pb – Pigeonholes, Continuums & Hybrid Deposits

- **VHMS–Epithermal** *shallow back-arc*
  - *Eskay Creek*
- **SHMS–VHMS –** *passive margins to complex back-arc basins*
  - *Filizchai (100 Mt at 4.5% Zn, 2% Pb)*
- **SHMS–Irish-type–MVT –** *extension to inversion to compression*
- **MVT–Manto & –Epithermal –** *late orogenic basinal to magmatic fluid systems at different crustal levels*
  - *Angouran, Oued Amizour*

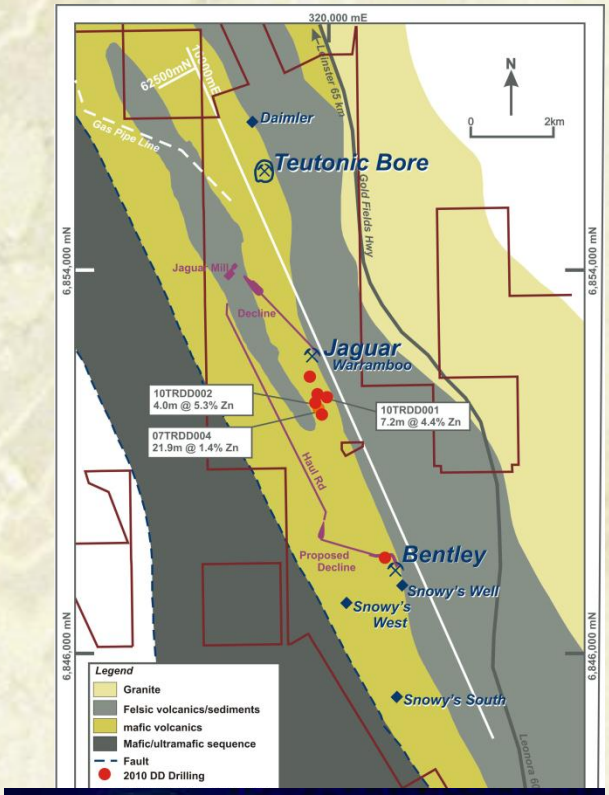


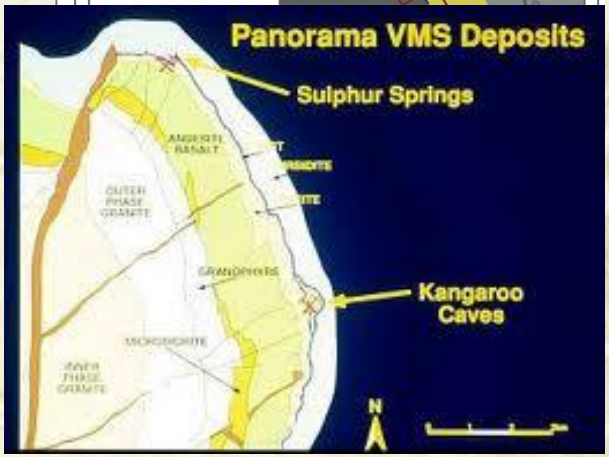
- **Significant unassigned deposits – which pigeonhole or continuum?**
  - *Elura, Abra, Woodcutters, Prairie Downs, Browns (Rum Jungle), Quidong*
  - *Kipushi, Couer d'Alene, Huize, Bawdwin, Rubiales*

Exploration models must be empirically-based and specific to each district and cognisant of variation within districts

Zn-Pb Discovery Opportunities – VHMS

- Unattractive for majors – size profile and mature districts – but polymetallic & precious metal credits ensure attraction for mid-tier or smaller companies.
- Exploration success has been driven by understanding of volcanic lithofacies, structure and alteration supported by geophysics (EM)
- New discovery opportunities:
  - in established districts with deep penetrating and down-hole EM.
  - in deeply weathered Archean and Proterozoic cratons, including Yilgarn.
  - in known districts without cutting-edge exploration – central Asia and China, Urals to Mongolia, Kunlun, Qilian; Arabian-Nubian shield.
  - new districts?
  - modern seafloor – Nautilus etc.





Zn-Pb Discovery Opportunities – SHMS & BHT

- Largest and most economi
  – opportunity for long-life p
  - *but* mature high-cost
    known districts
  - *and* BHT districts are
- Established targeting mode
  and "play-scale" explorati
  known fertile basins – e.g.
  requires commitment to lo
- Big company play ……
- ….. or find new or frontier
  opportunities:
  - e.g. N Tethyan margi
    Langshan, Qinling be
- Prospective belts can be i
  principals using fundamen
- Greater challenge when th
  and deformed (e.g. Sopok
  geochemical/outcrop discovery.

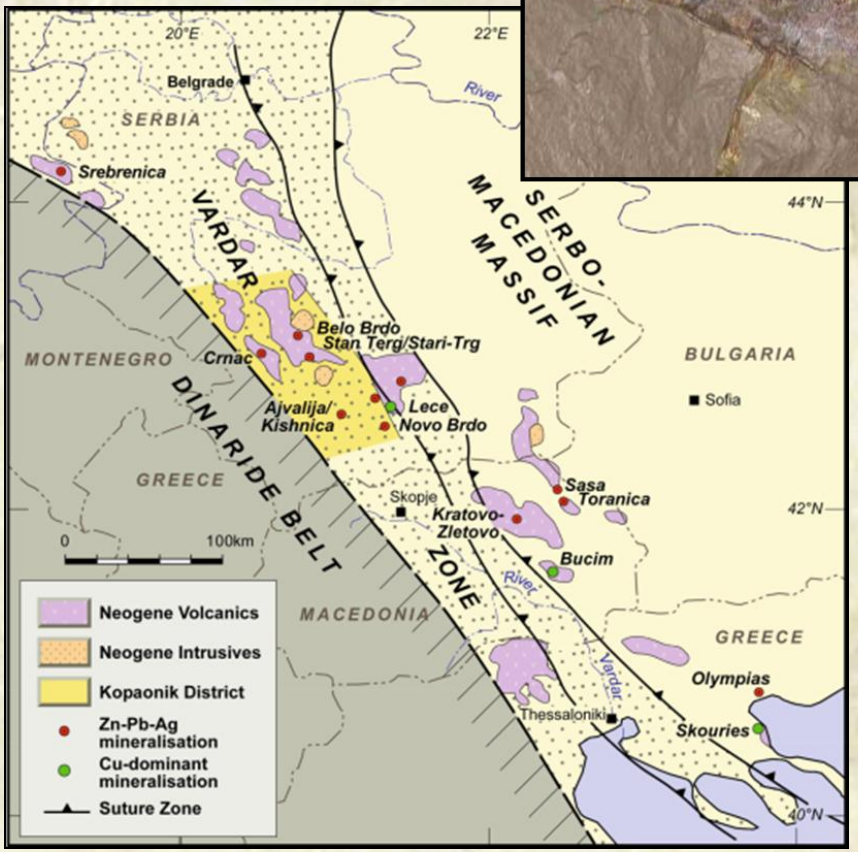
Zn-Pb Discovery Opportunities – MVT, Irish-type

- MVT unattractive for majors given low grades, but can deliver large scale projects
- Typically occur in large districts with extensive ‘smoke’ and geochemical anomalism; new districts unlikely to be discovered unless under cover
- Old districts – new potential for systematic exploration or new approach; e.g. N Africa Atlas belt; Silesia

- Irish-type economically attractive – large, high grade, & metallurgically favourable
- More common target than generally recognised
- Opportunities based on unrecognised districts – SE China, N Tethyan margin (Turkey, Iran, Pakistan).

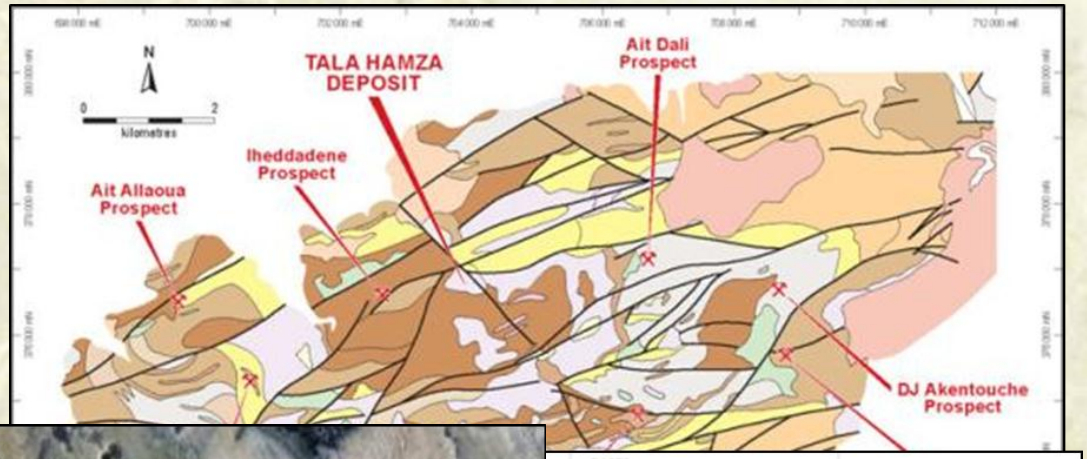
Zn-Pb Discovery Opportunities – Manto, Skarn & Epithermal

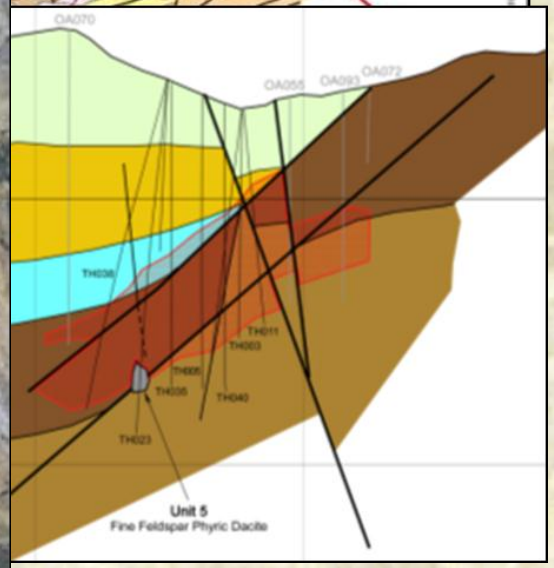
- Mantos can be large and high grade with silver and/or gold credits.
- Skarn and epithermal deposits can be huge but low grade, and overlooked – remaining potential in Cordillera.
- Outside Peru, Mexico & SE China, most known deposits are small, often irregular poddy and difficult to explore – unrealised potential?
- Calc-alkaline arcs with young carbonates – e.g. Indonesia, Laos-Thailand, NE China
- Potential in neglected old districts – Vardar belt, Balkans; Trepča belt 80 km long, 5 mines, > 4 Mt Zn+Pb and c. 120 Moz Ag



Zn-Pb Discovery Opportunities – Hybrid & Unconventional

- Many hybrid or “unconventional” deposits are poorly understood and targeted
- Extensional late orogenic hybrids – Jinding (c. 200 Mt at 6.1% Zn, 1.3% Pb), Angouran (14.6 Mt non-sulfide ore at 22% Zn and 4.6% Pb), Oued Amizour (68.6 Mt at 4.6% Zn and 1.1% Pb) etc.
- Kipushi-type in sedimentary copper settings
- Zn silicate in Neoproterozoic basins.





Conclusions

- Discovery of Zn-Pb has been in a downward spiral, limited grass-roots exploration.
- Looming Zn supply gap & Pb renaissance driven by renewable energy demand.
- Demand partly met (at a cost) by:
  - *increased recycling,*
  - *metallurgical processing of problematic ore (e.g. Dugald River, Gamsberg),*
  - *development of remote resources (e.g. Selwyn Basin, Citronen Fjord).*
- New discovery opportunities exist and can be capitalised on using an approach combining target understanding and new technology, for example:
  - *targeting from first principals in identification of new regional plays and opportunistic follow-up first pass reconnaissance;*
  - *basin analysis targeting in known fertile basins, especially for SHMS and Irish-type;*
  - *VHMS targeting by EM and geology in poorly tested belts or challenging weathering environments;*
  - *new target types, such as hybrid epithermal-MVT deposits in pull-apart basins in collapsed orogens.*
  - *manto, skarn and epithermal in Tethyan and W Pacific arcs*

Conclusions

- Consider targeting on scales from regional to district to deposit.
- Empirical targeting criteria must be ahead of model-driven.
- Must be developed for each trend, district or region to take account of variability and hybrid settings, e.g. Lennard Shelf MVT.

- Interesting recent “non-conventional” discoveries or developments include Dome 5 (3m @ 15.8% Zn, 4.0% Pb, 63g/t Ag) and Prairie Downs (13m @ 6,5% Zn, 6.1% Pb, 162g.t Ag)

- Discovery history of deposits like Sopokomil provides a salutary lesson on finding unexpected deposit types in unrecognised target terrain.

- Opportunism – give luck a chance – serendipity of discovery.