IX CONGRESO INTERNACIONAL DE PROSPECTORES Y EXPLORADORES

proEXPLO 2015

INVERSIÓN EN EXPLORACIONES: Base del Desarrollo Minero Sostenible

Lima, del 18 al 20 de Mayo

Sheraton Lima Hotel & Convention Center

ORGANIZA:

INSTITUTO DE INGENIEROS DE MINAS DEL PERÚ

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The Mineral Systems Approach: Key to Predictive Exploration Targeting

Jon Hronsky[1,2] and Cam McCuaig[2]

WESTERN MINING SERVICES

Centre for EXPLORATION TARGETING

1. Western Mining Services and 2. The Centre for Exploration Targeting (UWA and Curtin University)

Key Messages

- Predictive targeting requires an organising framework – the Mineral System approach
- Ore deposits are part of a much larger system
- Ore-forming systems show diverse chemical processes but a much narrower range of *physical* processes – focusing on these is the key to predictability
- Mineral systems are complex dynamic systems, exhibiting self-organised critical (SOC) behaviour
- Critical elements of mineral systems are whole lithosphere architecture, transient favourable geodynamics, fertility, and preservation
- Mineral systems have different expressions at different scales

The Problem

- **More and more of the world we explore in looks like this – need to become more predictive!**

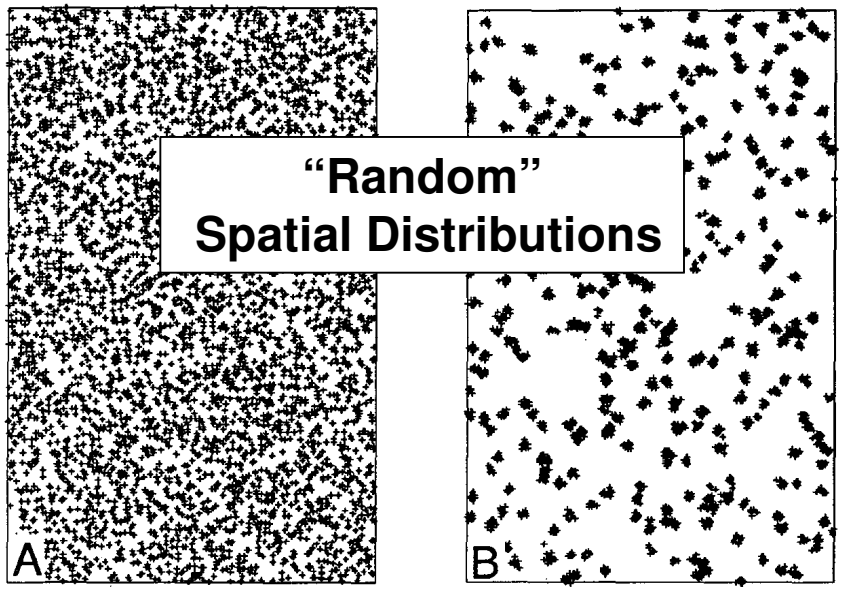
Are Mineral Deposits Predictable?

Two views:

1. **Ore deposits are the product of a "lucky" conjunction of various random geological processes (ie inherently unpredictable!)**

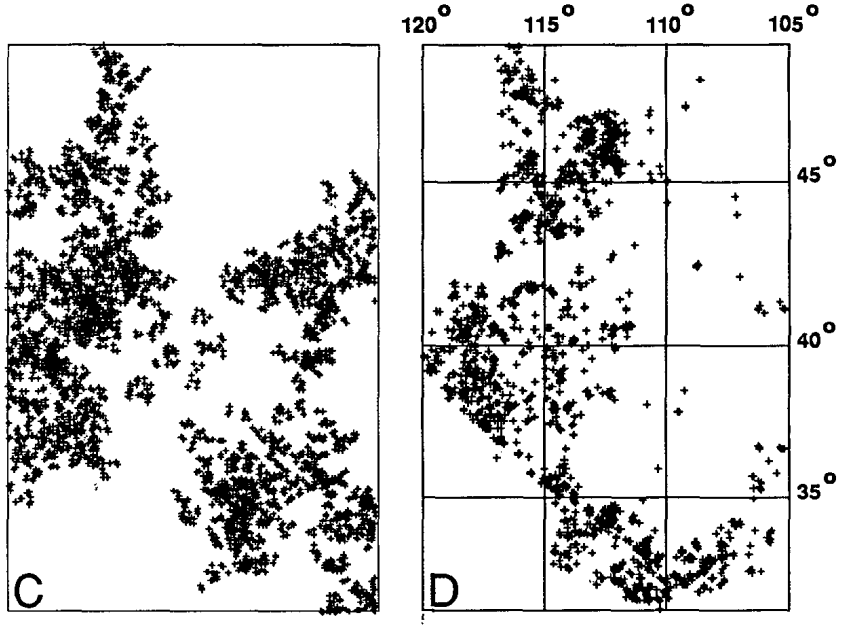
2. **Ore deposits are the *rare but predictable* outcome of the geological evolution of active terranes**

Carlson (1991)



"Random" Spatial Distributions

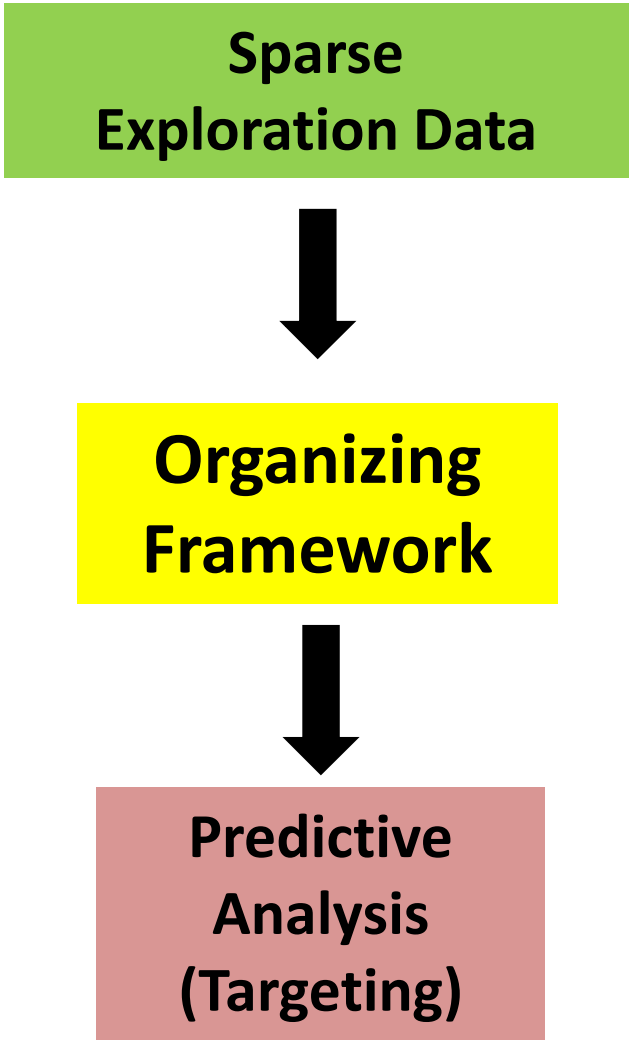
Fractal Spatial Distribution



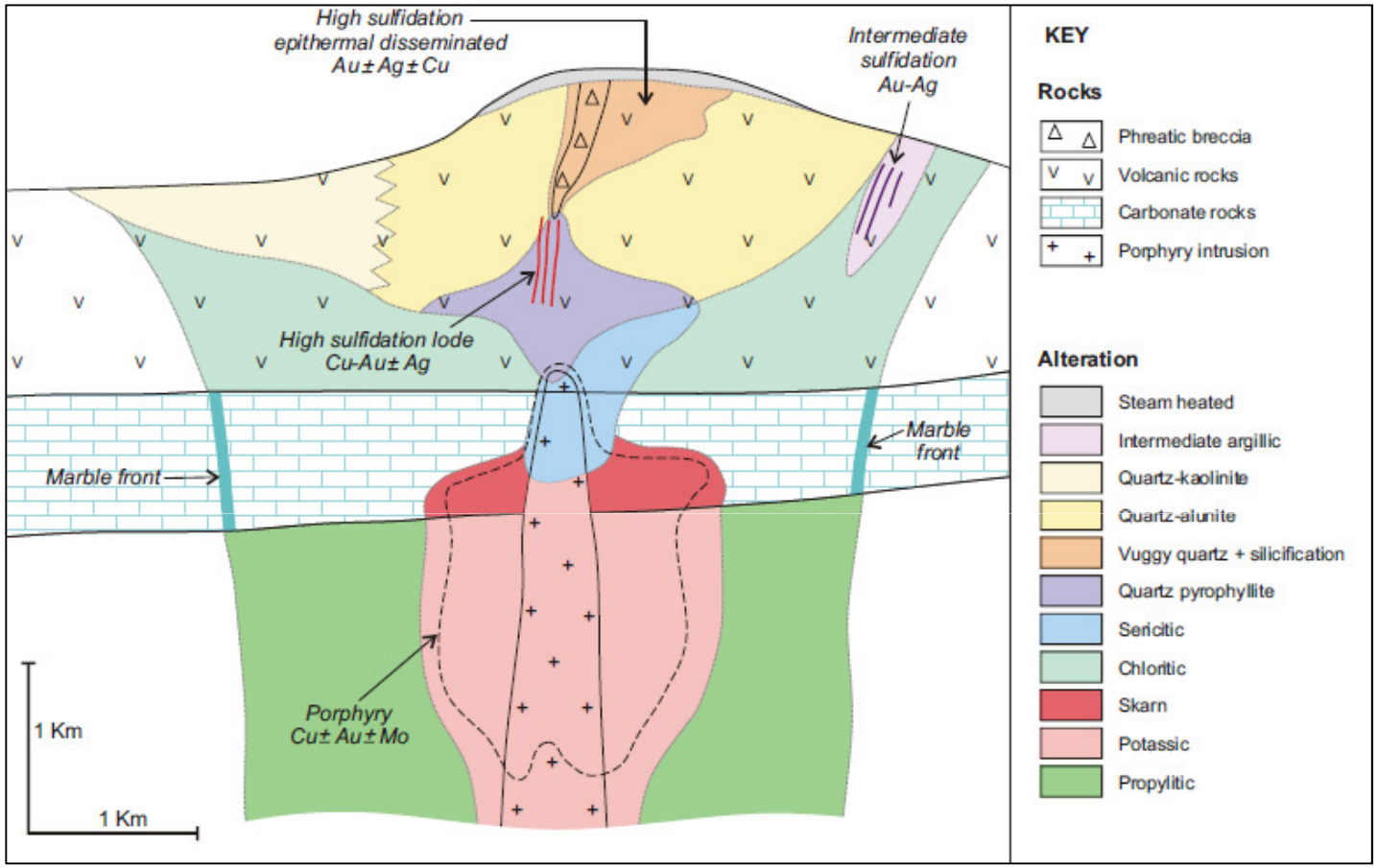
Precious Metal deposits of the Great Basin, Western US

Ore Deposit Distributions are Ordered not Random!

The need for an Organising Framework



Example of a Successful Organising Framework



after Sillitoe (2012)

...but how to expand beyond the deposit scale?

The Answer - The Mineral Systems Concept

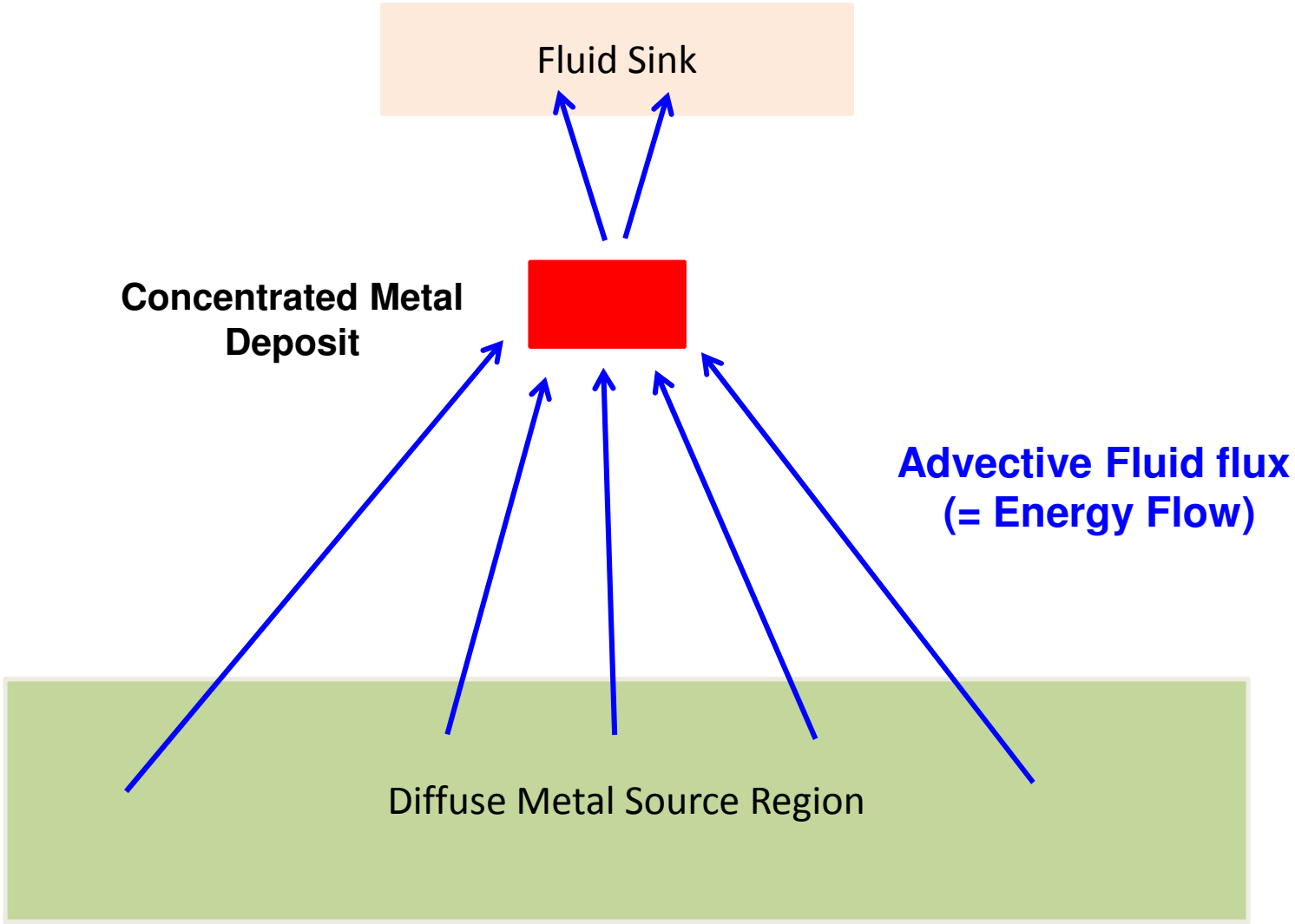
Mineral deposits = expressions of large-scale earth processes focussing energy and mass transfer at a range of nested scales

The “Mineral System” is that collection of multi-scale processes

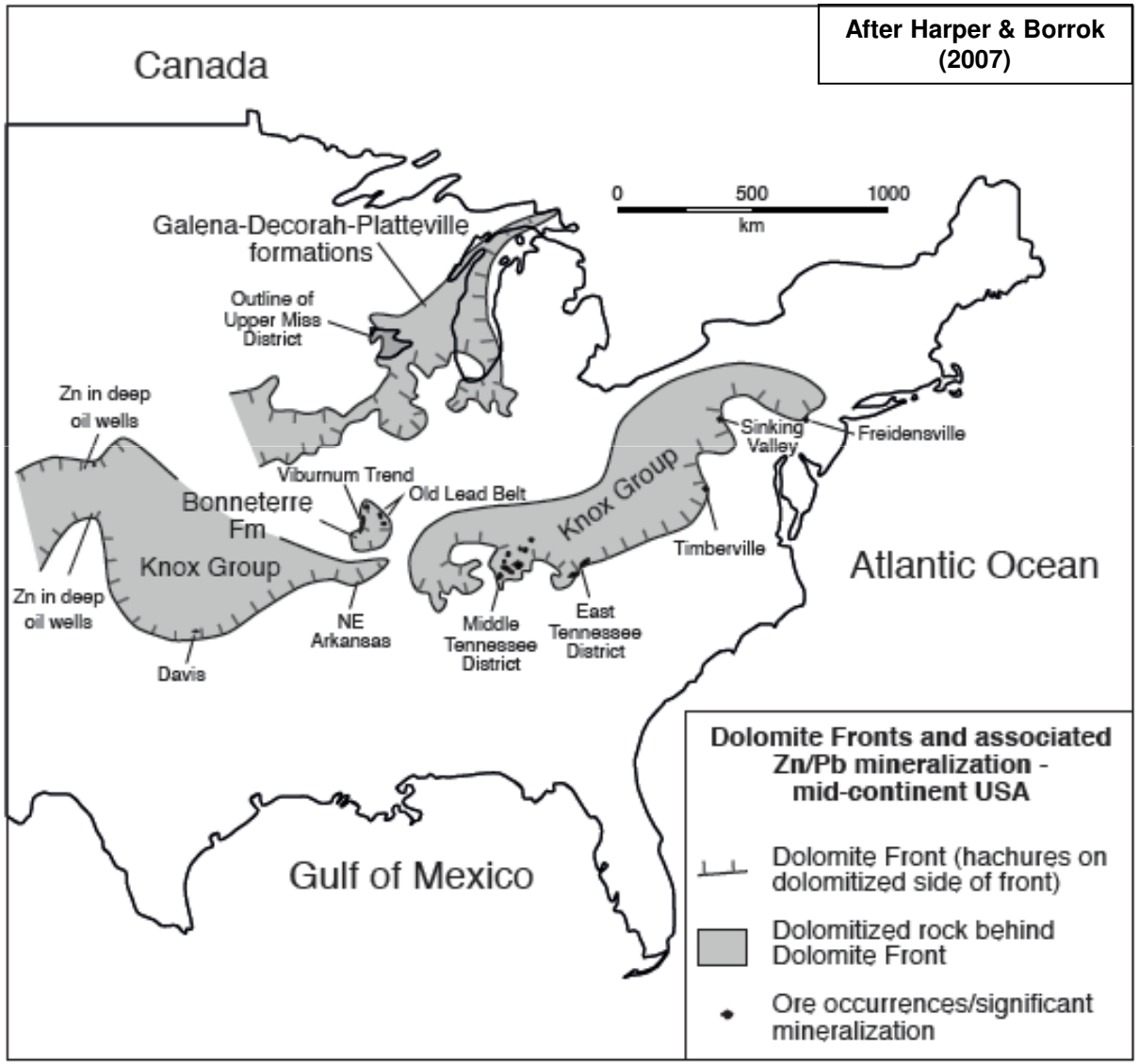
Supports prediction in data-poor environments, compared to traditional approaches based on analogue deposit models

Examples of Application: Yeelirrie Calcrete U, Olympic Dam Cu-U-Au, Nebo Babel NiS

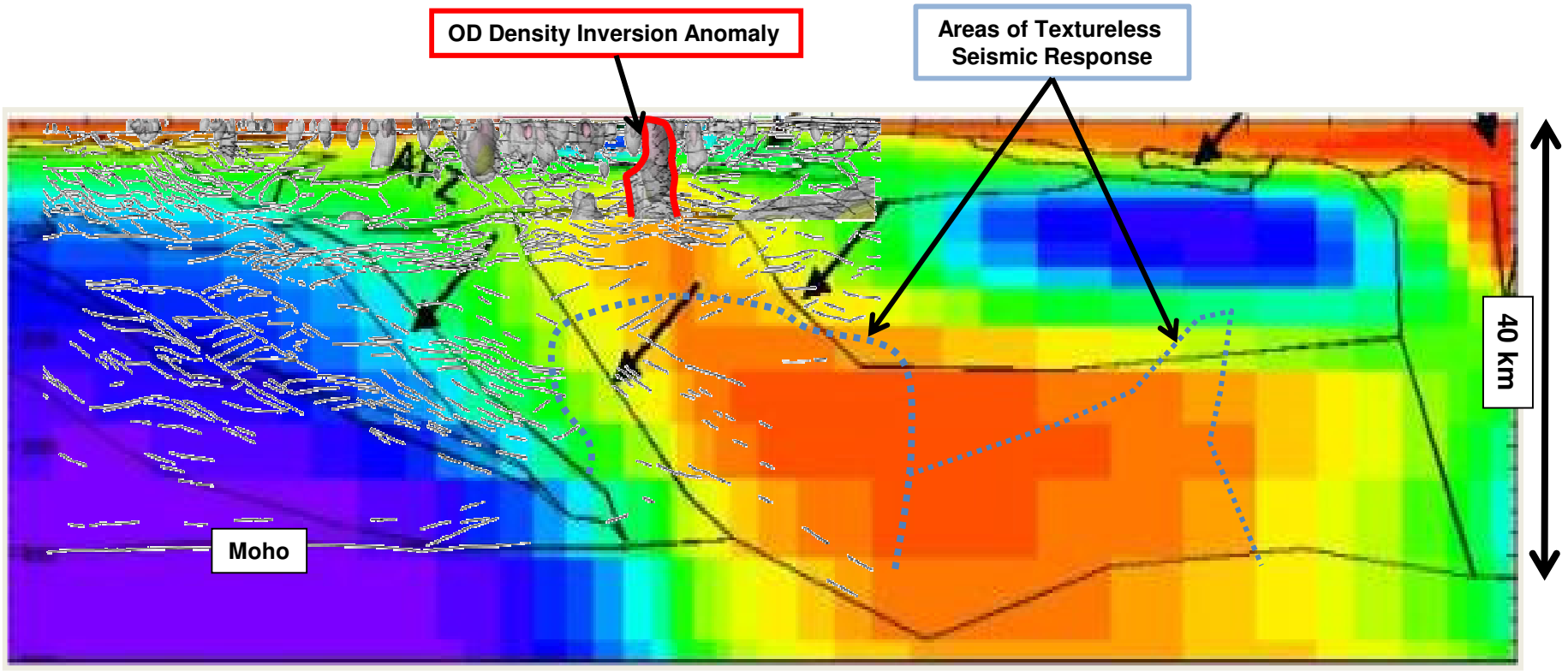
Basic Physics of Ore Formation



Mineral Systems may have very large-scale footprints

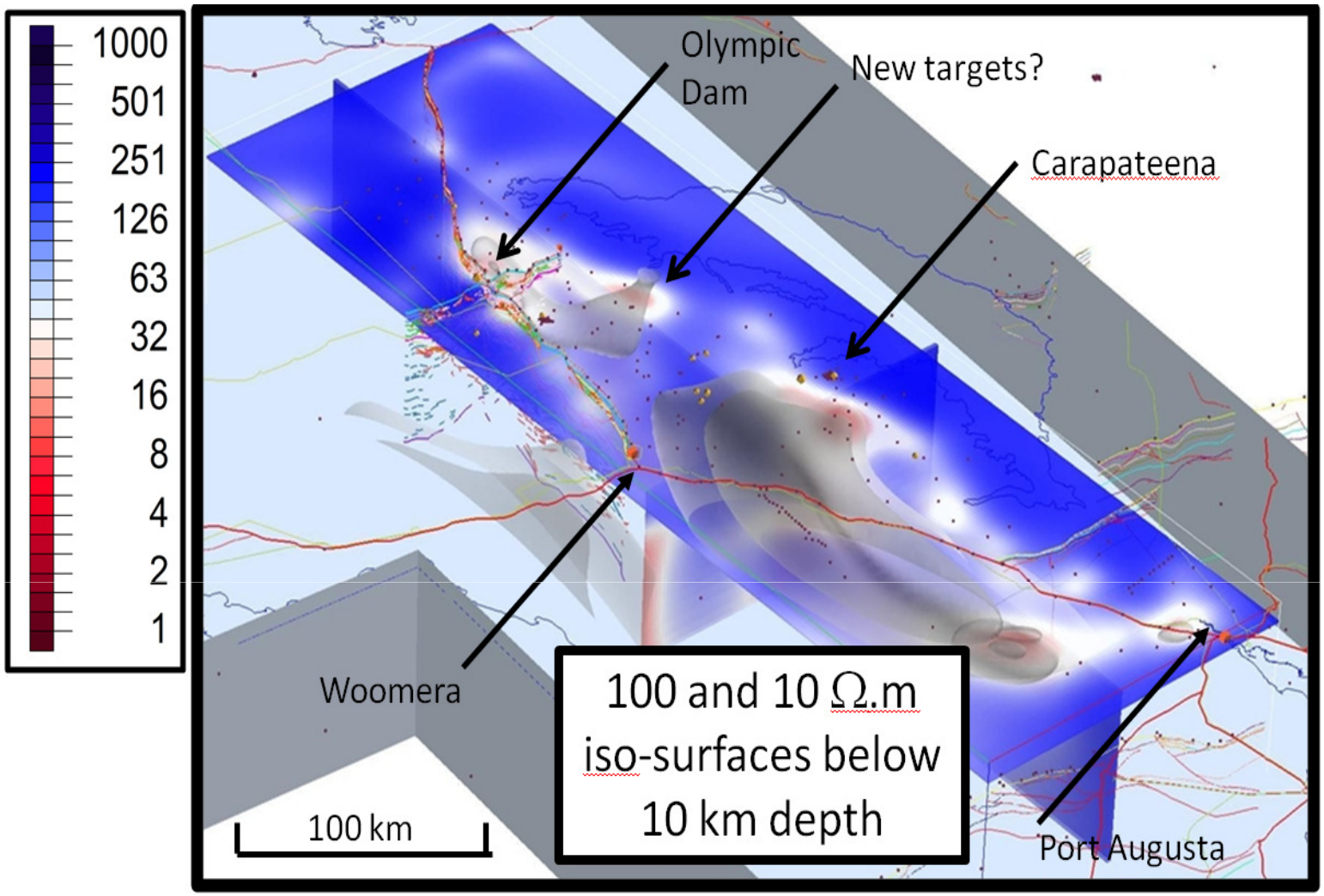


We need to look deep to understand many systems



Magnetotelluric Section through Olympic Dam

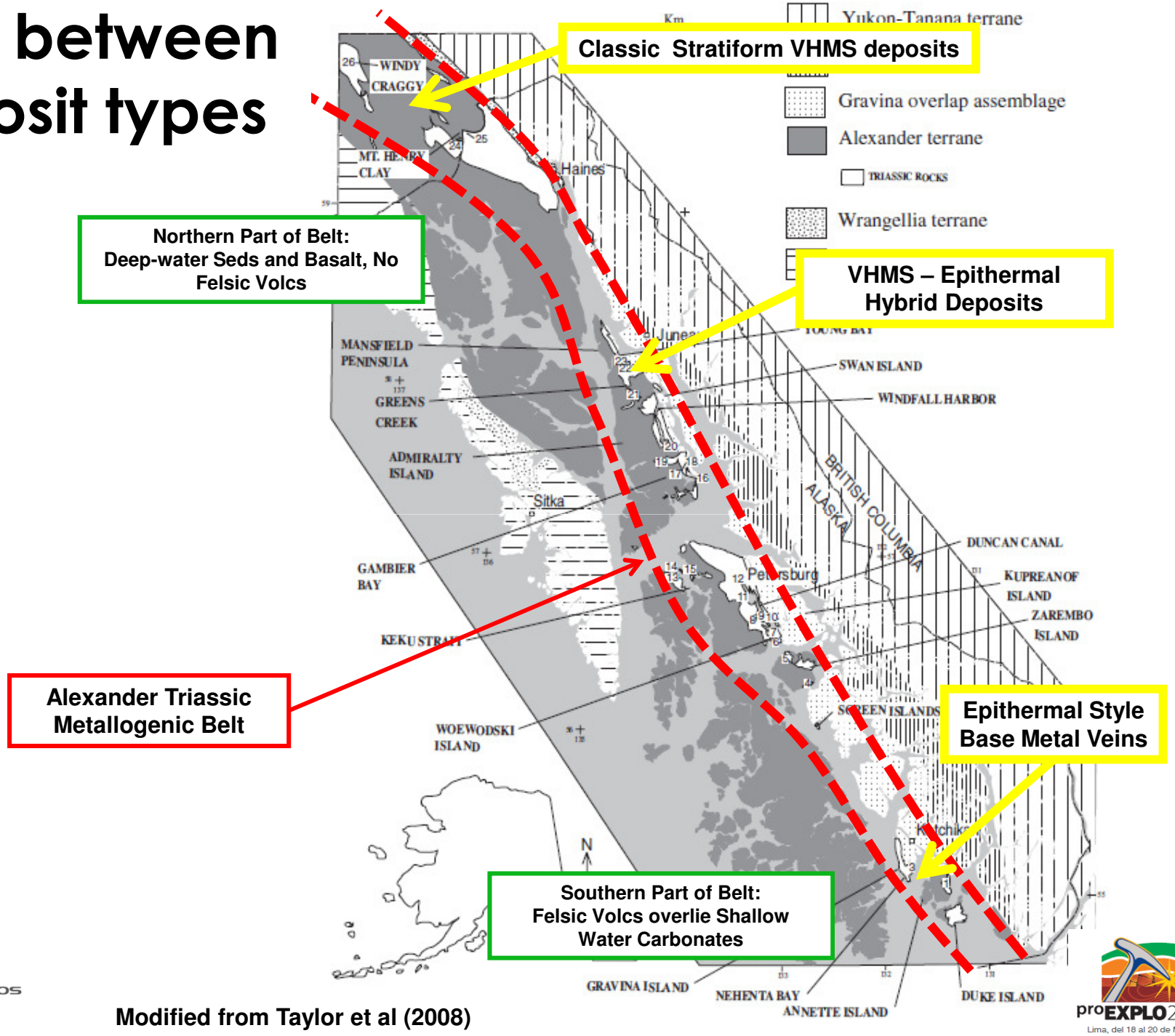
Modified after Hayward, 2004; Magnetotelluric data from Graham Heinson; "hotter" colours are more conductive



We are starting to learn how to image source-regions and how they link to deposits – MT Data from the Gawler Craton

Heinson (2014)

Links between deposit types



Modified from Taylor et al (2008)

Mineral Systems are highly dynamic

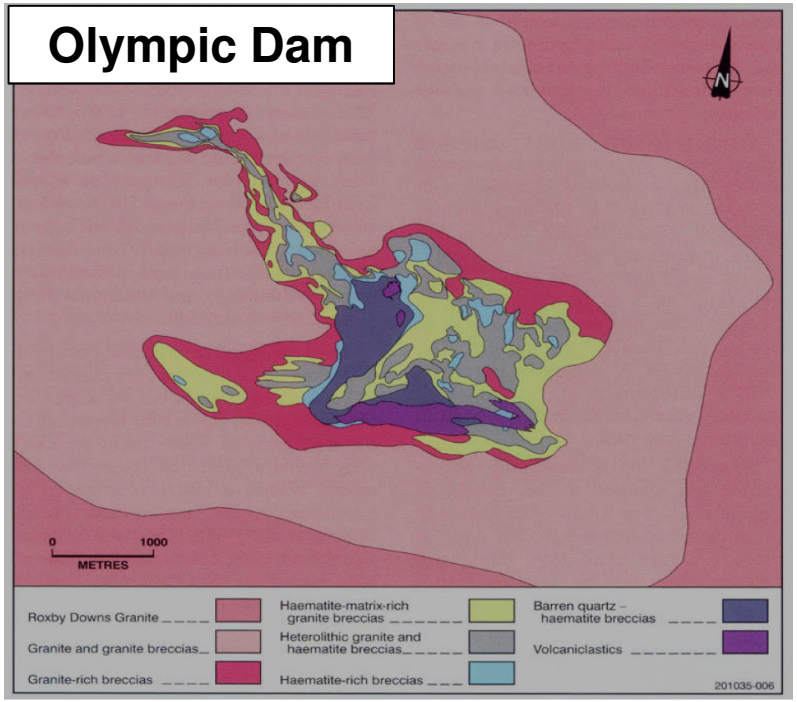
Take elements at low concentration from large volumes of rock to high concentration in small volumes of rock

Only plausible mechanism is through advective mass flux – needs a fluid (fluid/magma)

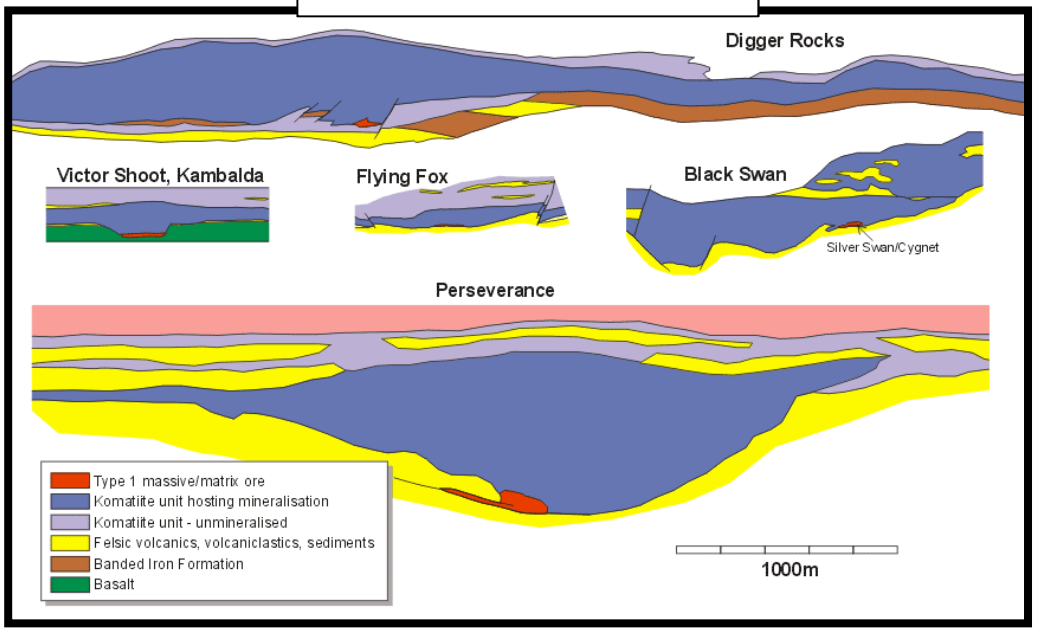
Ore deposits therefore are foci of large scale advective mass and energy flux

Fluid needs to be low viscosity, available in large quantities over short timeframes, highly organised (focussed in space and time)

Olympic Dam



Perseverance Ni



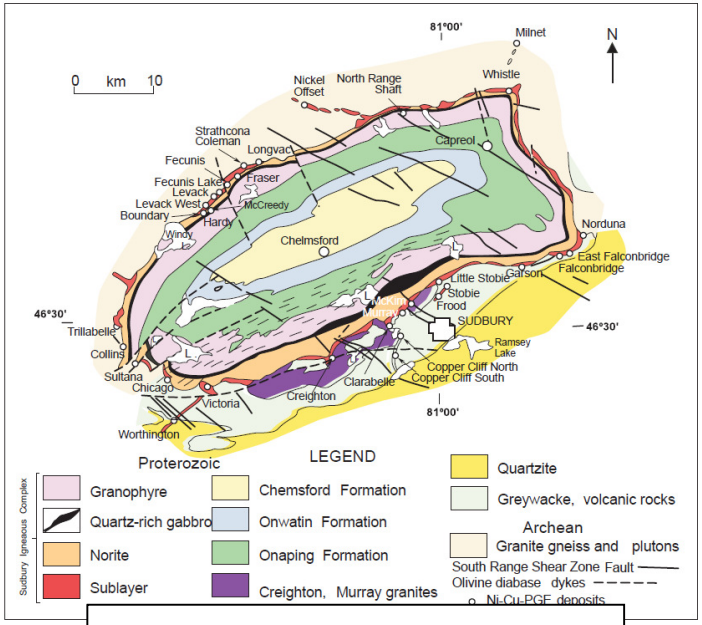
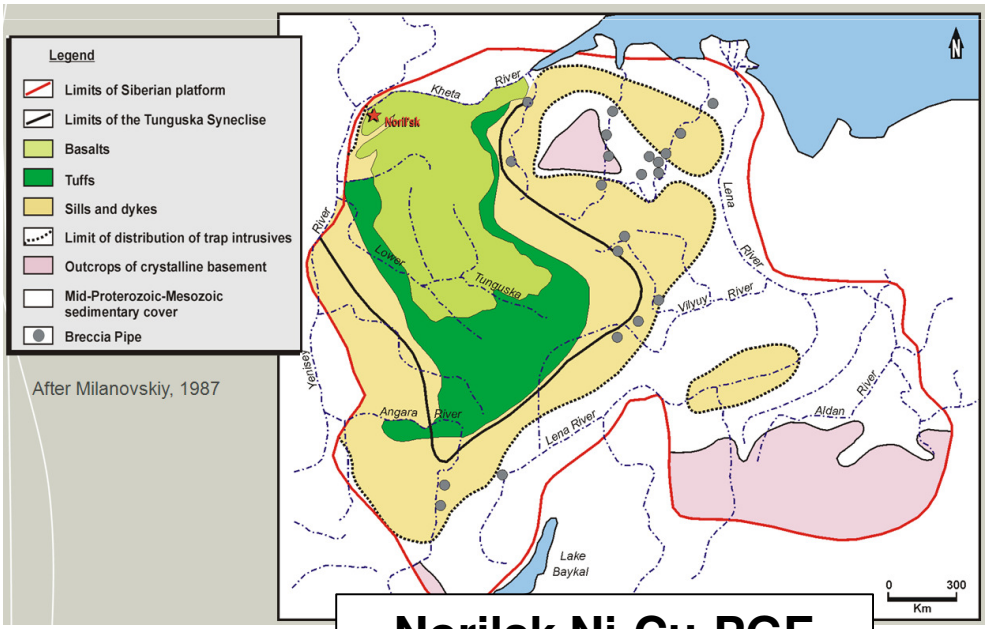


FIGURE 5. Sudbur ad Schwerdtner, 1991).

Sudbury Ni-Cu-PGE

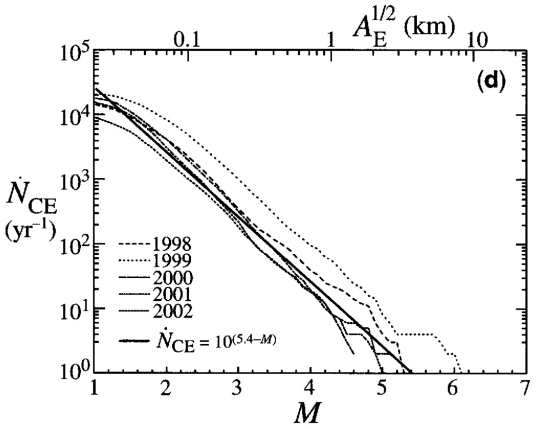


Norilsk Ni-Cu-PGE

Self-Organisation in Earth Systems

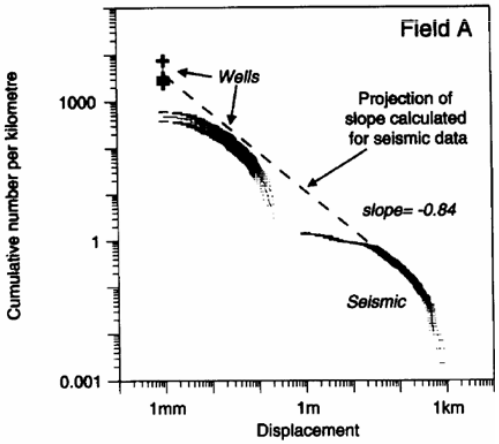
Power-law size frequency distributions (scale invariant)

***Example:* Gutenberg-Richter earthquake scaling**



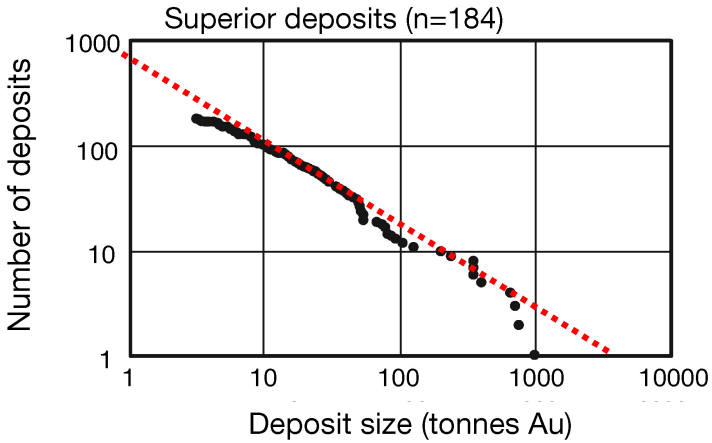
Malamud & Turcotte 2006

***Example:* Fault size populations**



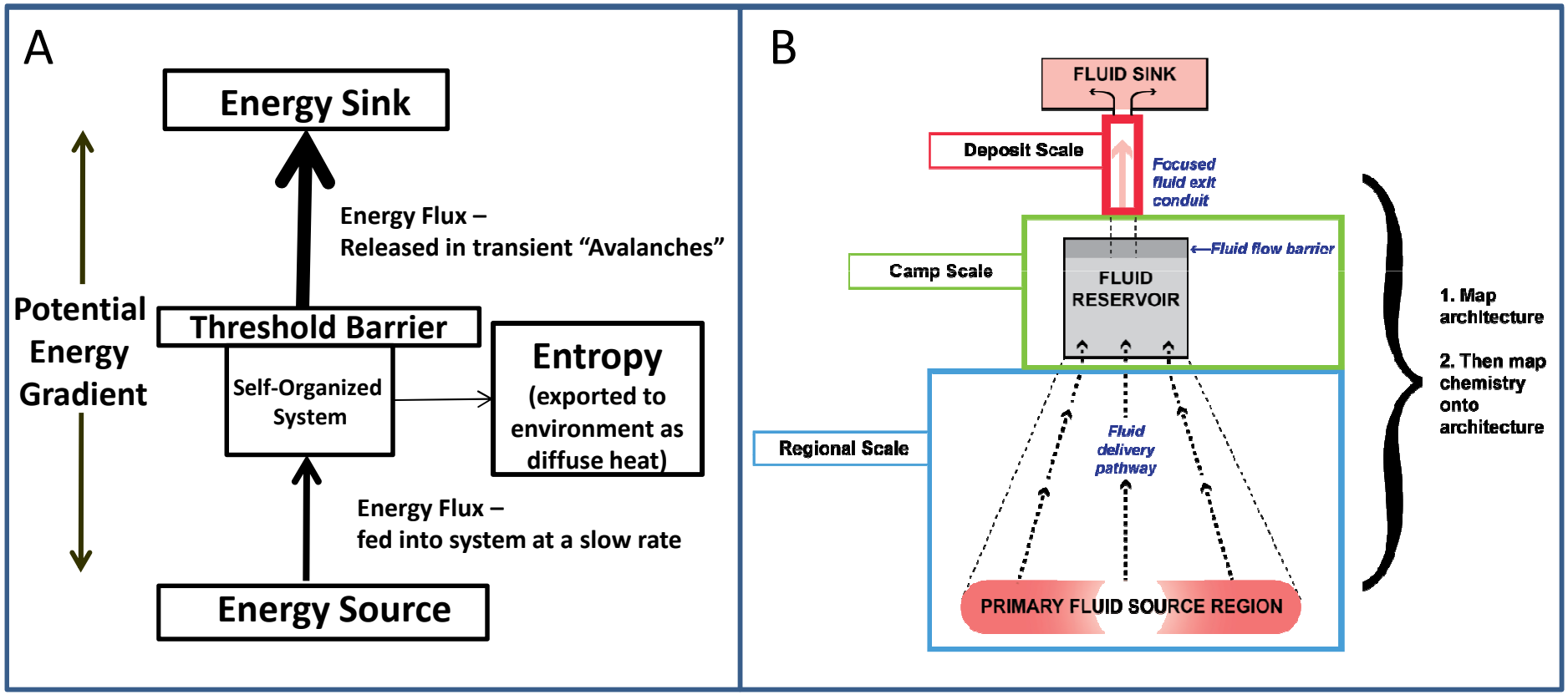
Needham et al., 1996

***Example:* Superior craton, greenstone-hosted lode gold**



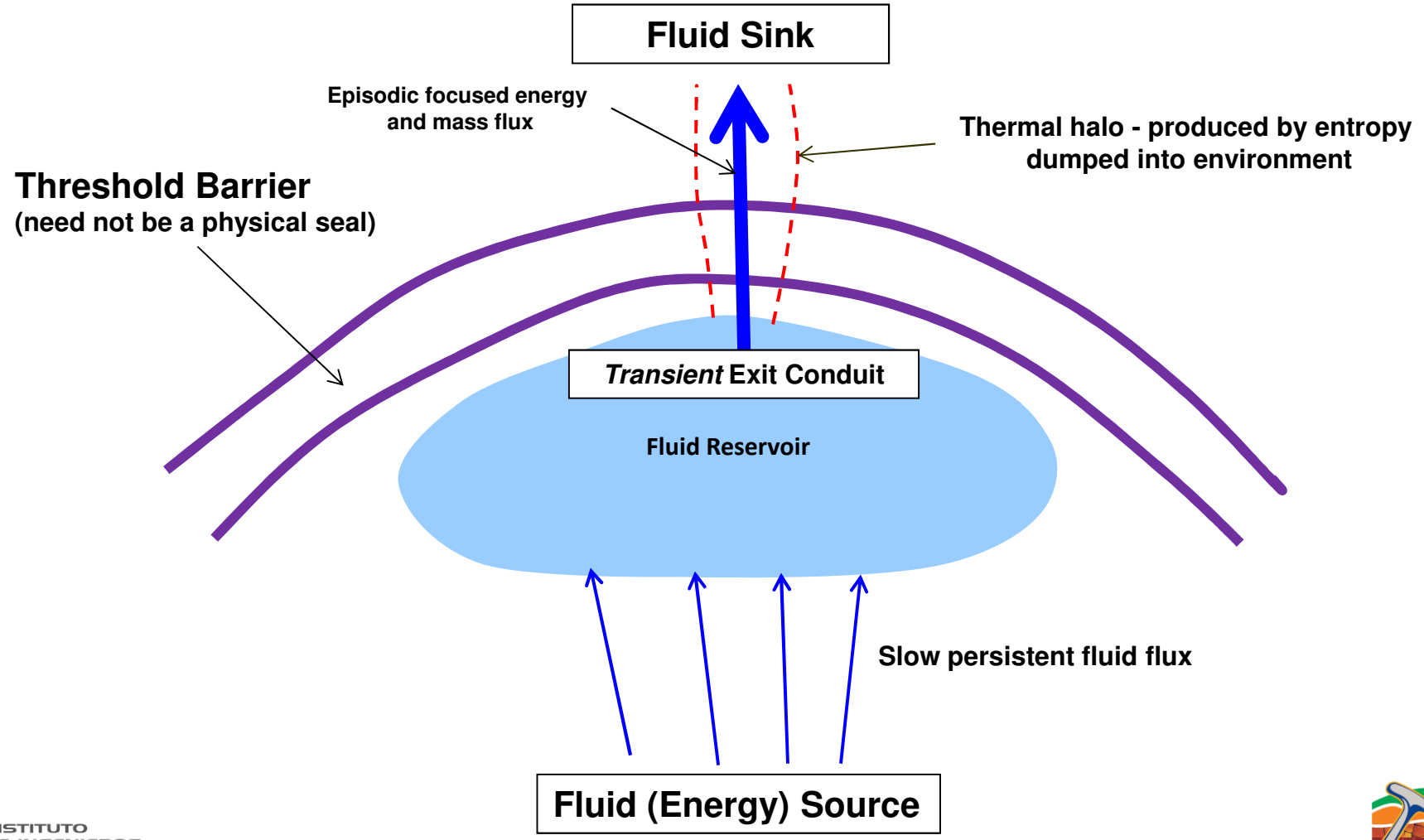
Robert et al., 2005

Ore formation as a product of Self-Organising Critical Systems



McCuaig and Hronsky, 2014

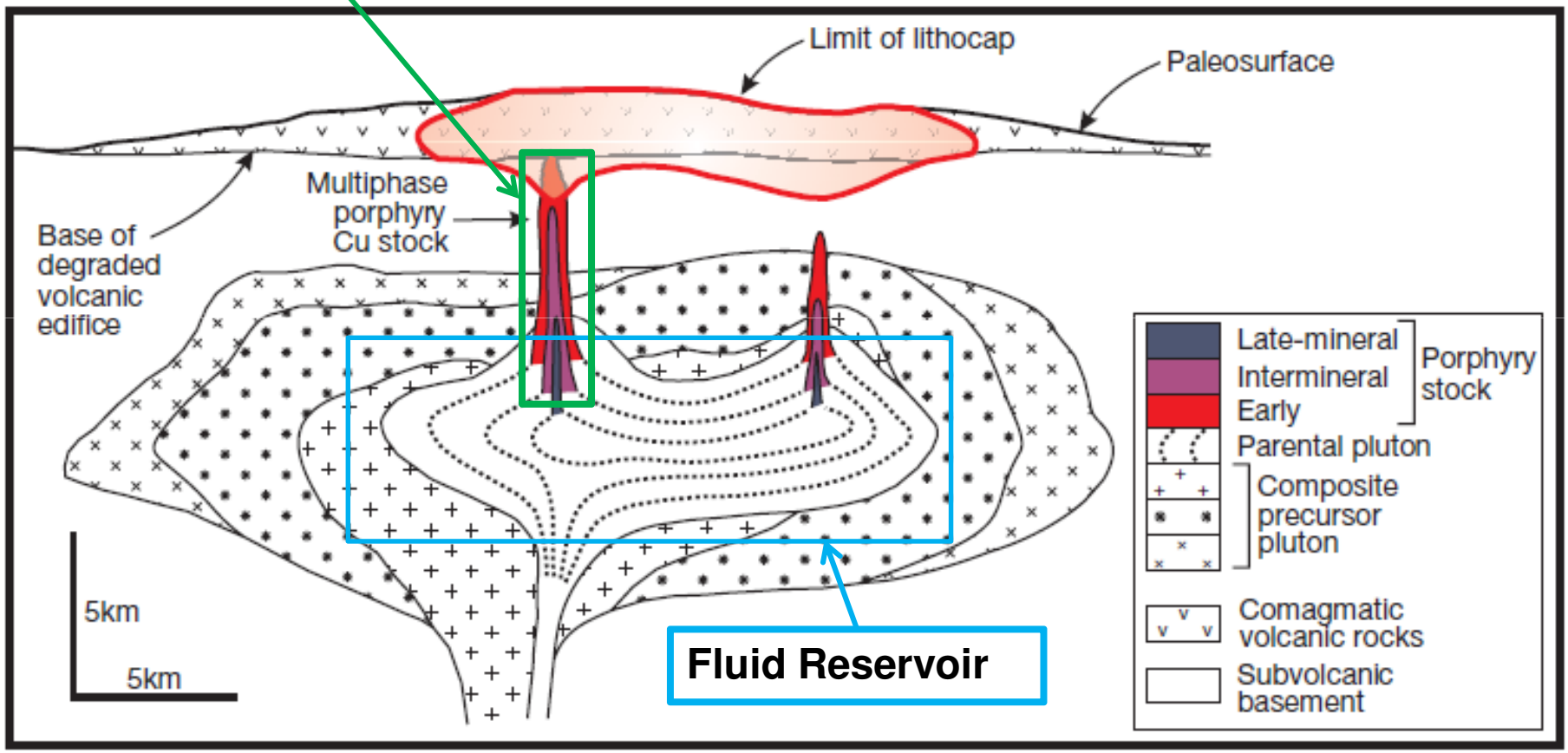
Key Concept: Fluid Flow system dynamics are de-coupled above and below the “Seal”

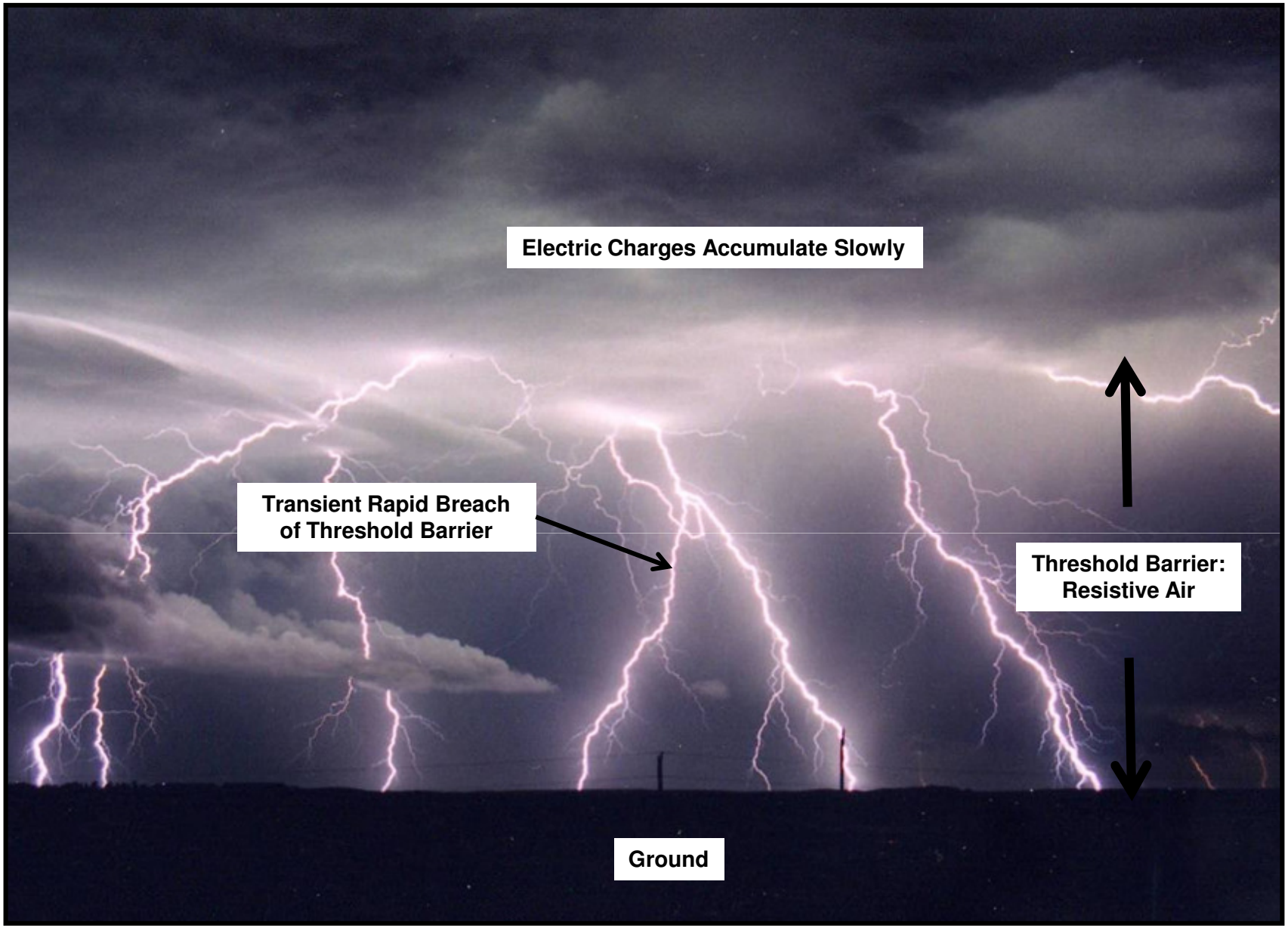


Porphyry Cu Example

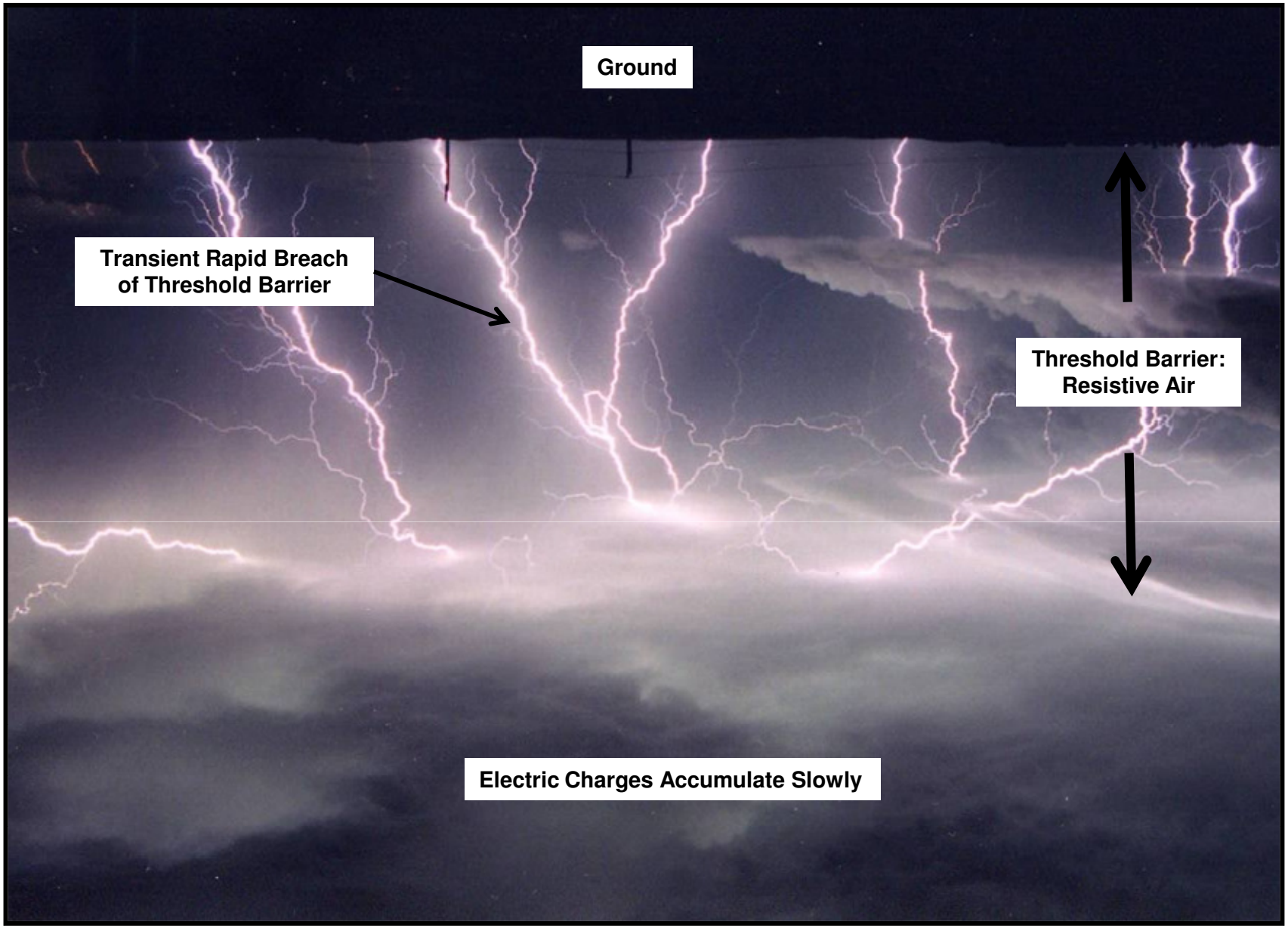
Fluid Exit Conduit

From Sillitoe (2010)





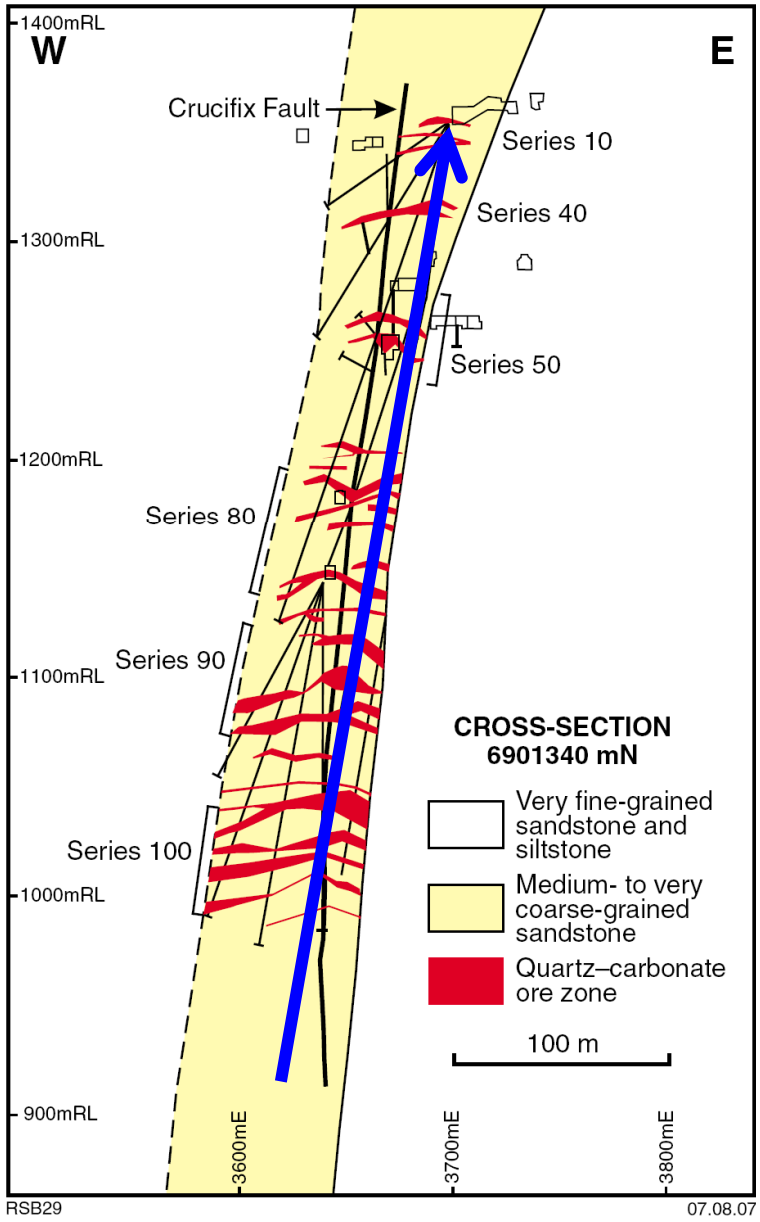
The Lightning Analogy for Ore-Forming Systems

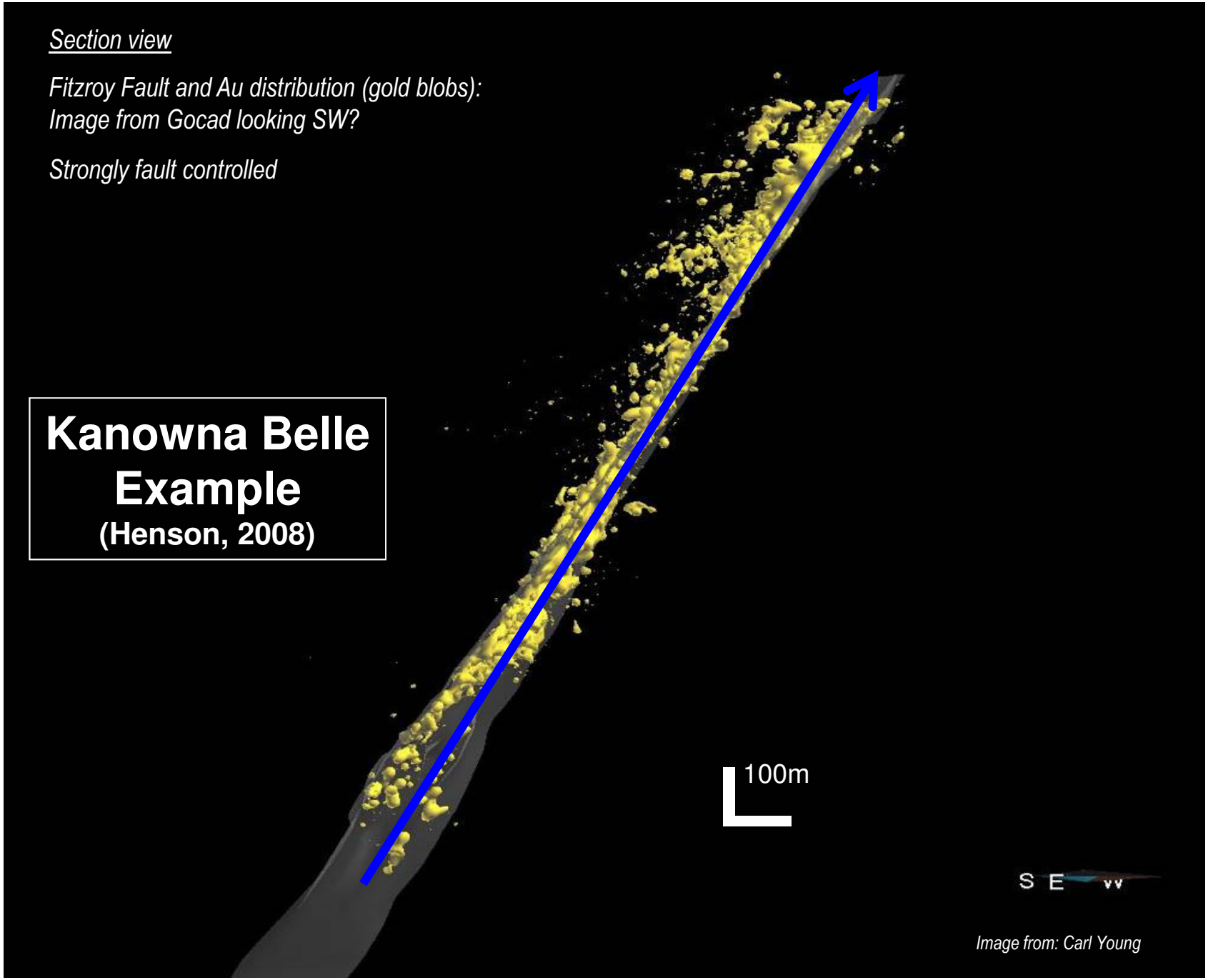


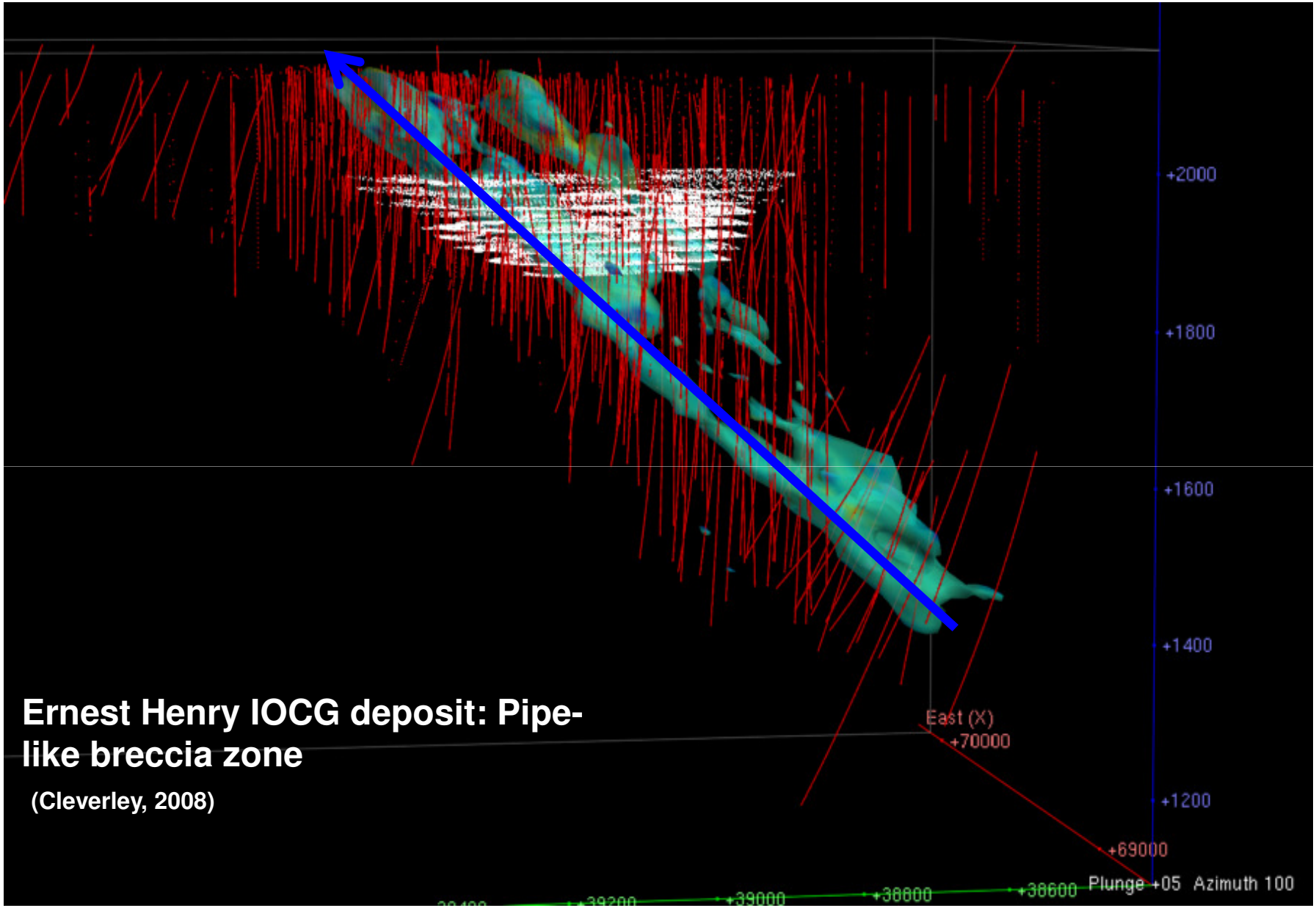
The Lightning Analogy for Ore-Forming Systems

Examples of Fluid Exit Conduits

New Holland Au:
(Henson, 2008)

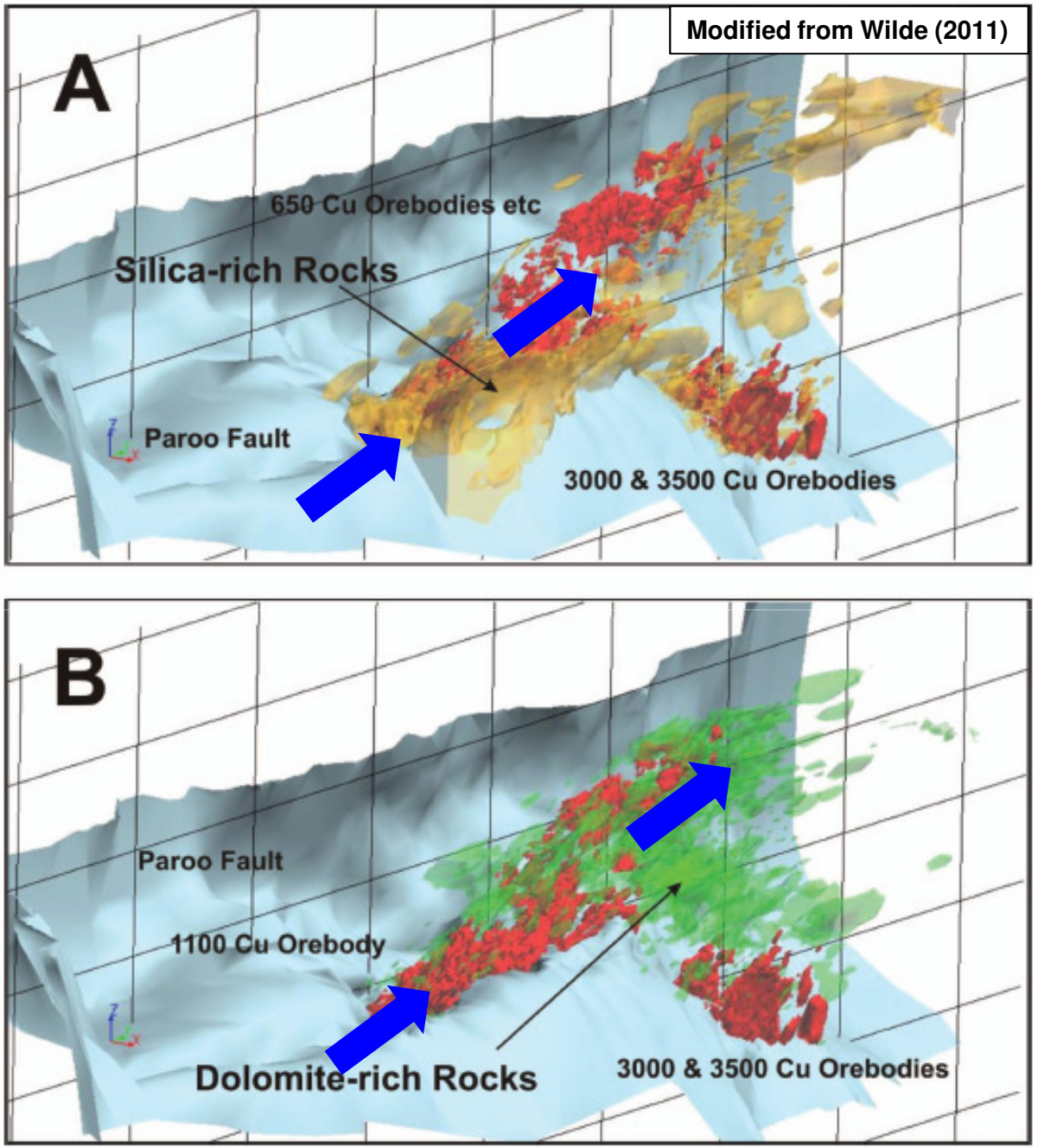



Section view
Fitzroy Fault and Au distribution (gold blobs):
Image from Gocad looking SW?
Strongly fault controlled
Kanowna Belle
Example
(Henson, 2008)
100m
S E
Image from: Carl Young



Ernest Henry IOCG deposit: Pipe-like breccia zone

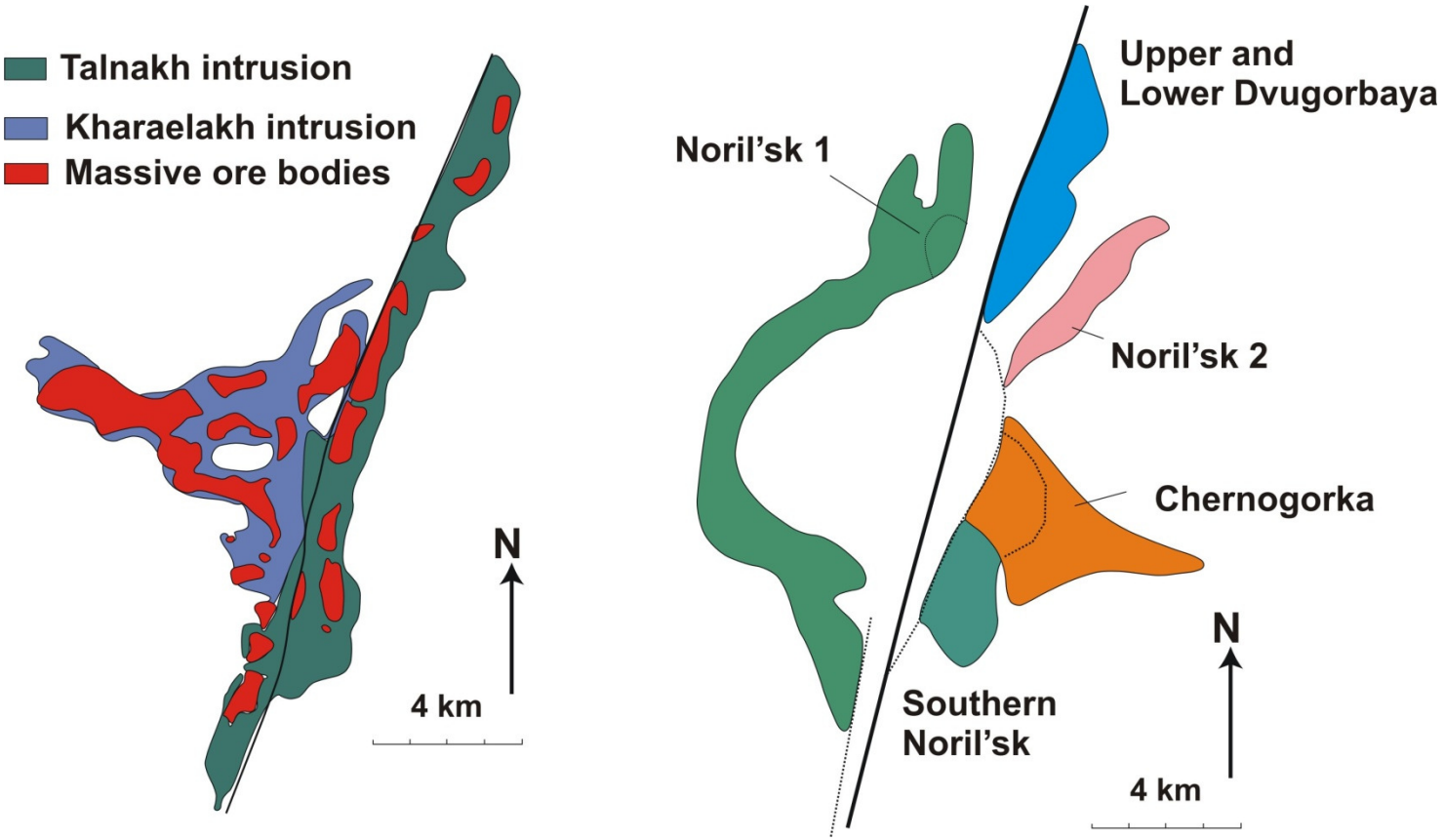
(Cleverley, 2008)



Inferred Major Ore-fluid Conduit at Mt Isa

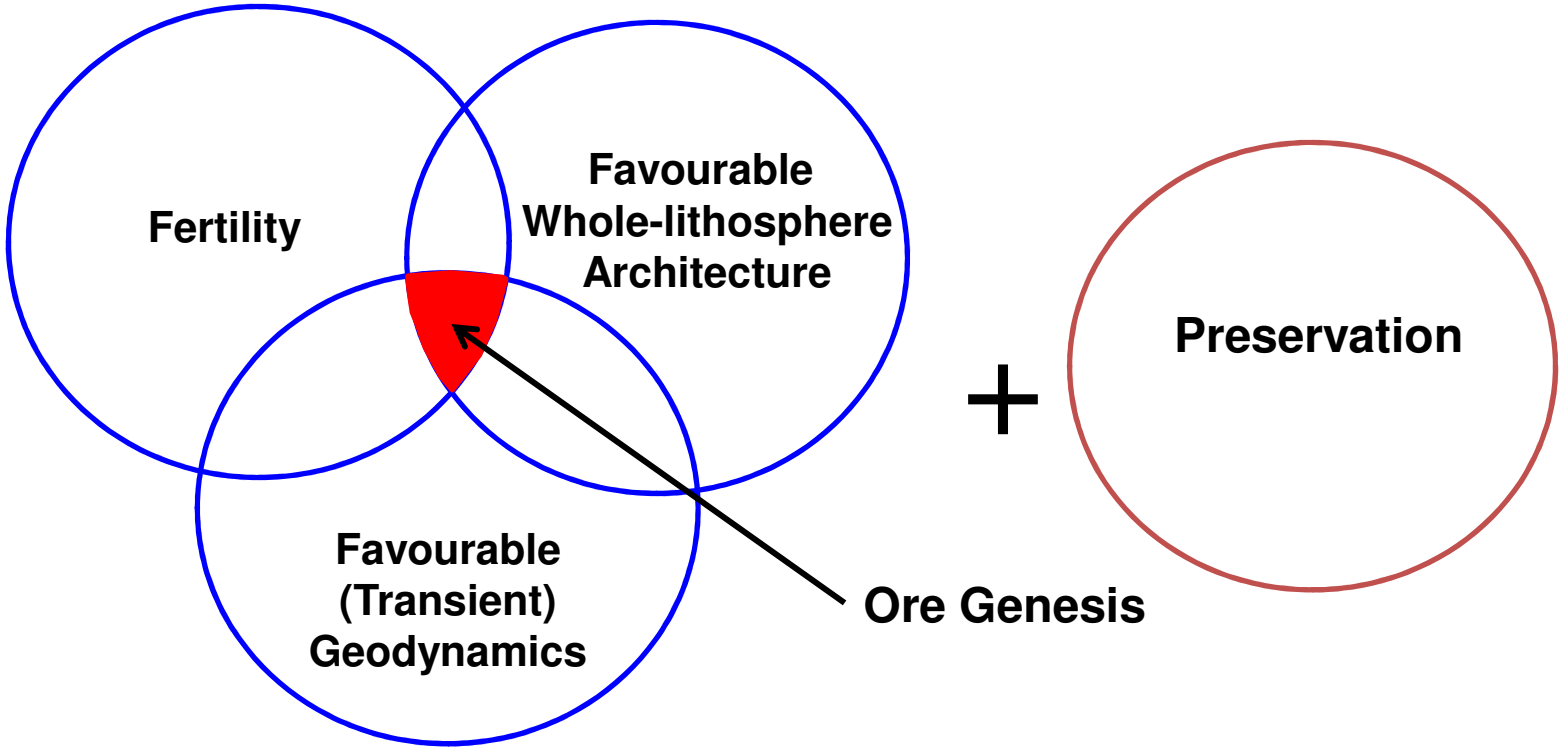
Chonoliths are Magmatic Examples of Fluid Exit Conduits

Examples of Chonoliths from the Noril'sk Camp

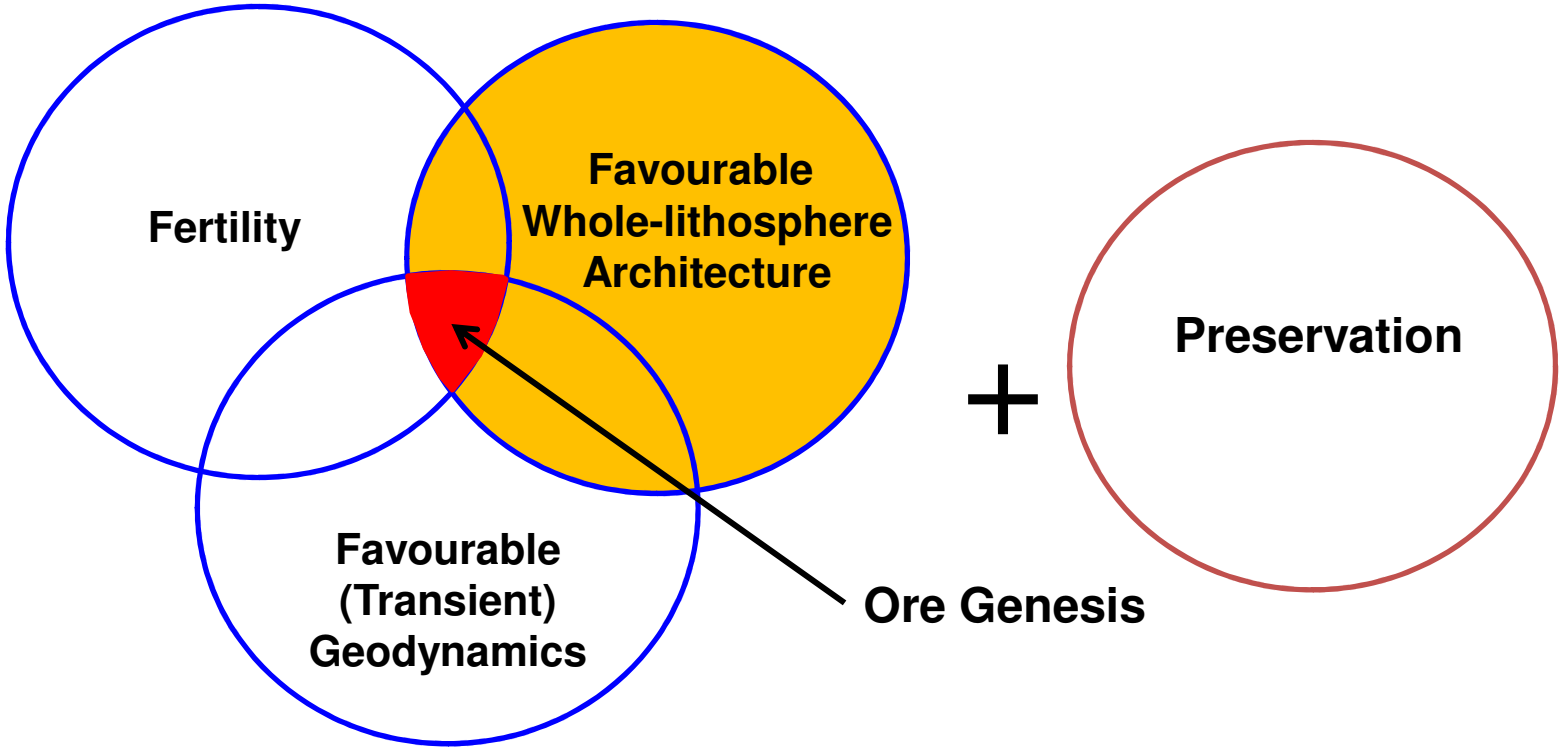


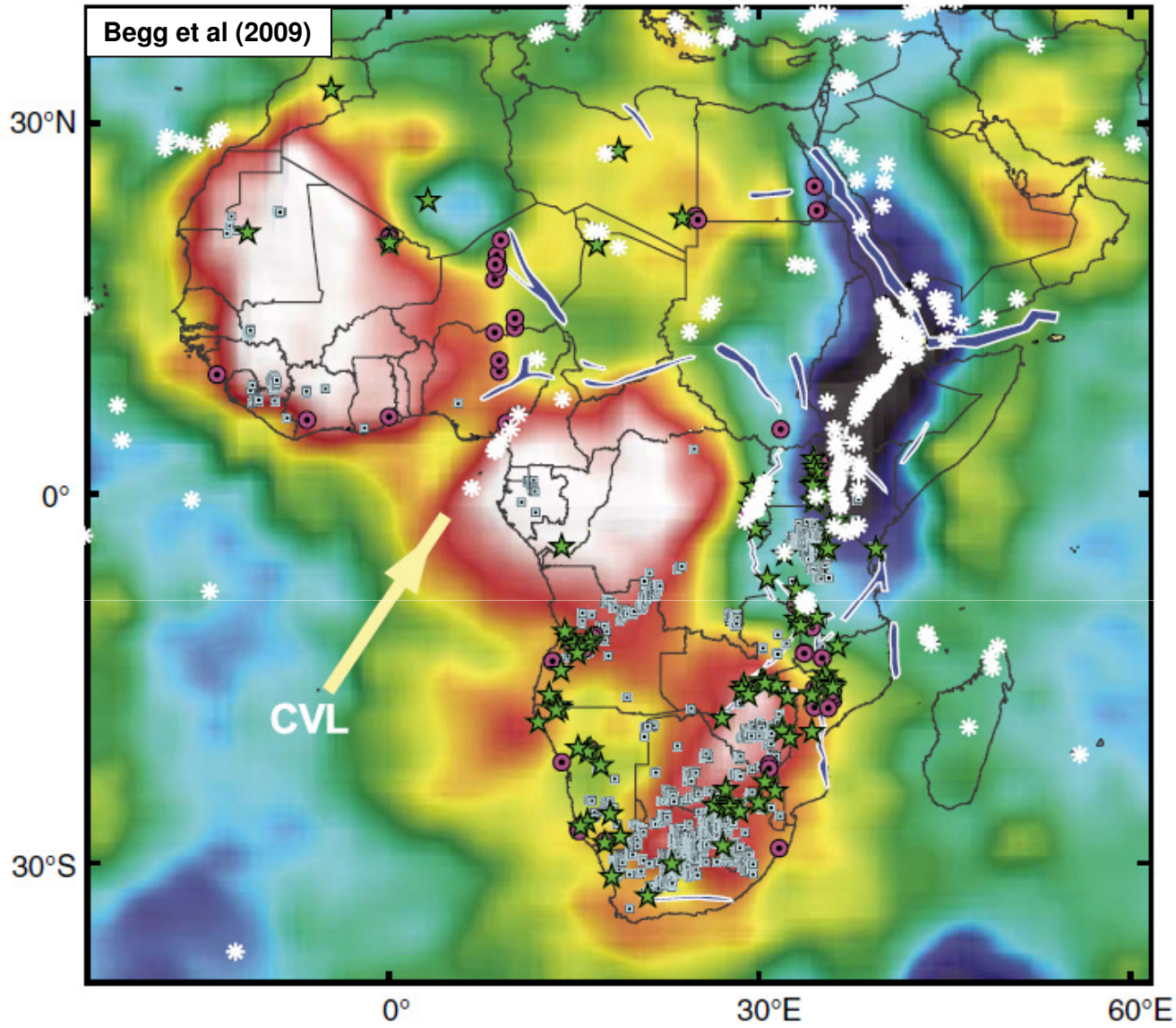
Zen'ko and Czamanske 1994

Critical Elements of Mineral Systems



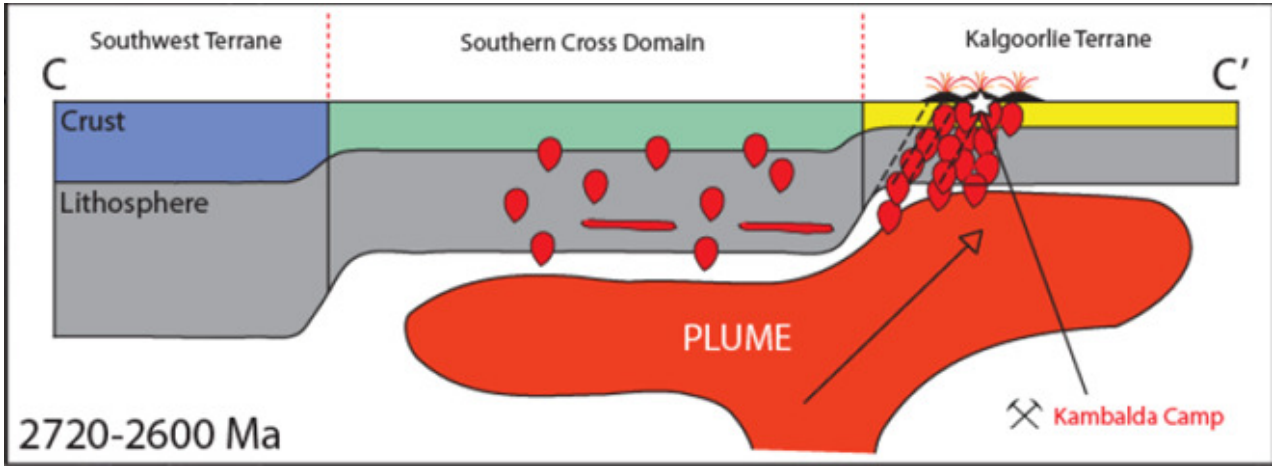
Critical Elements of Mineral Systems



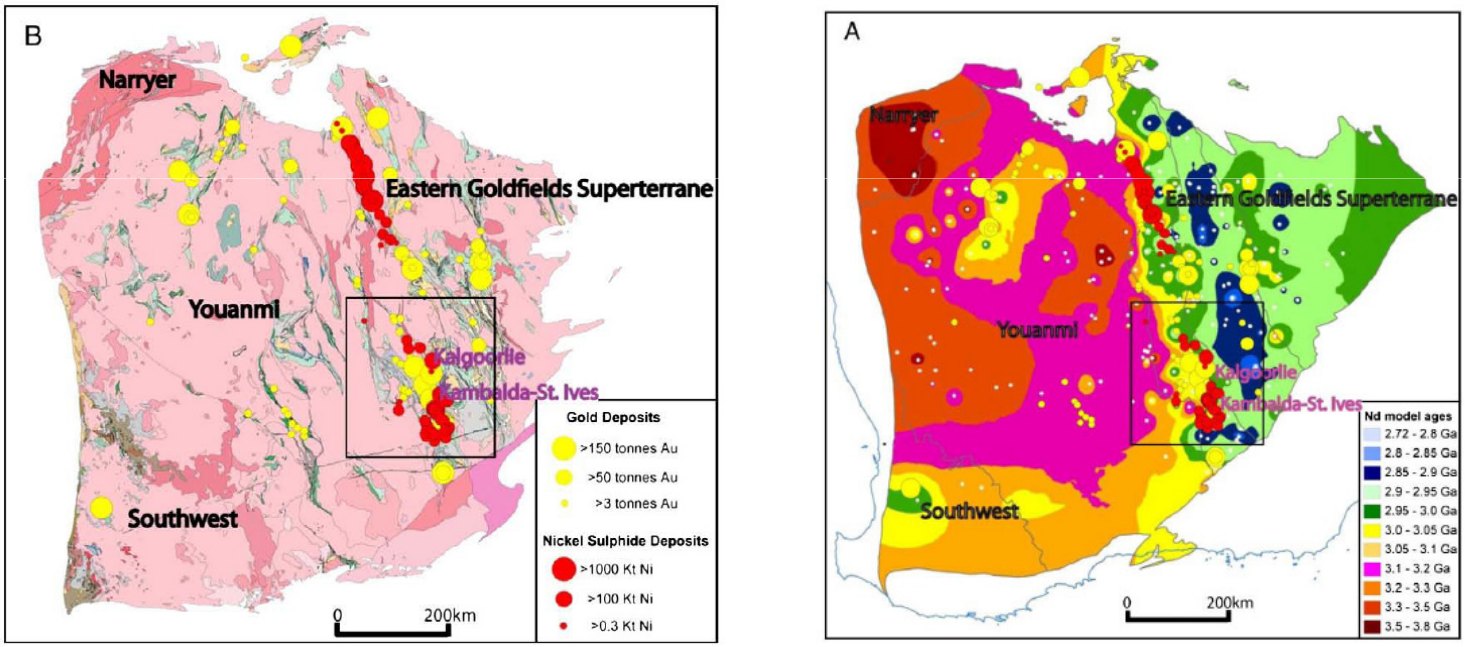


Lithospheric Architectural Control on Mantle-Melting and Rifting in Africa

Background image is Vs seismic tomography for 100-175km depth slice; blue polygons = recent rifts; white asterisks = modern volcanos; green stars=carbonatites; pink circles=nepheline syenites; white squares=kimberlites; CVL= Cameroon Volcanic Line



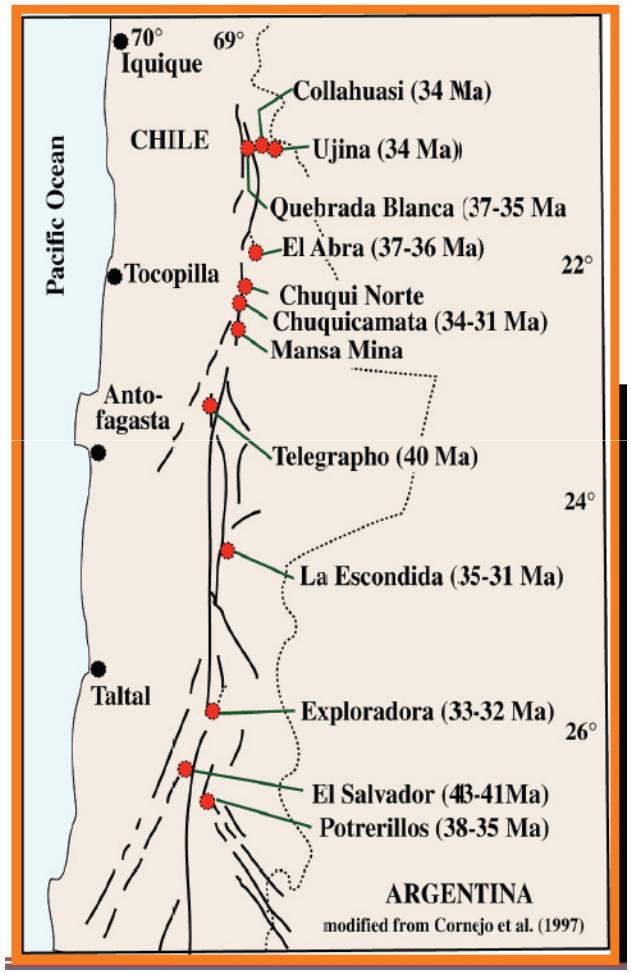
Mole et al (2012)



McCuaig et al. (2010); Sm-Nd map from Cassidy & Champion (2004)

Lithospheric Architecture: Key Metallogenic Control

A fundamental association- ore deposits and major basement structures



Domeyko FZ
Tosdal (2009)

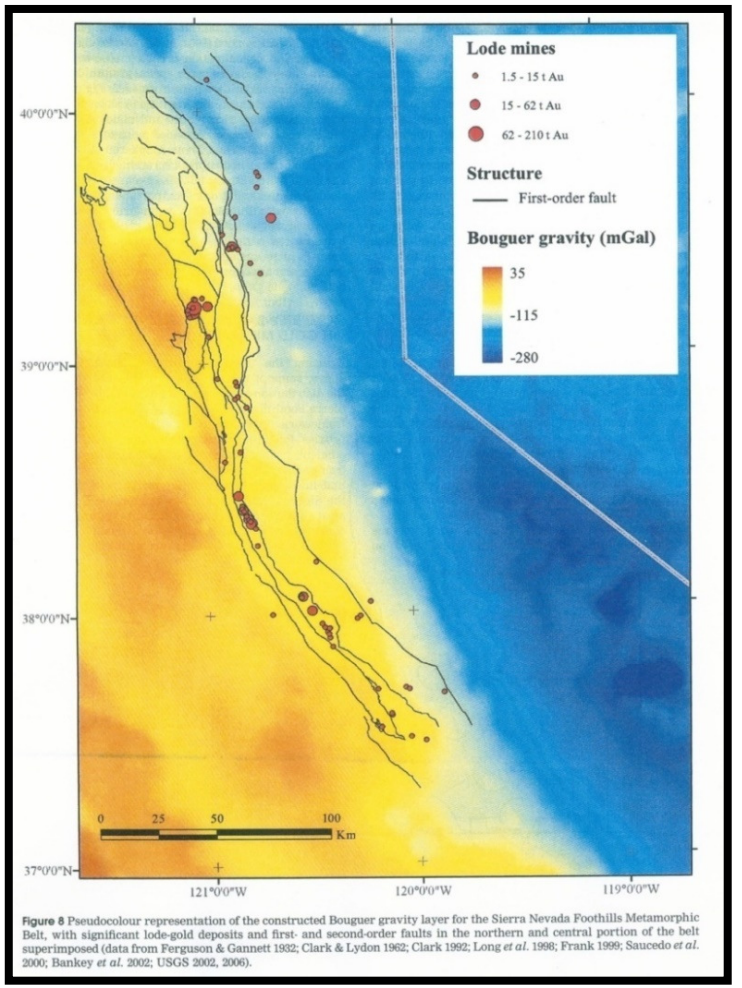


Figure 8 Pseudocolour representation of the constructed Bouguer gravity layer for the Sierra Nevada Foothills Metamorphic Belt, with significant lode-gold deposits and first- and second-order faults in the northern and central portion of the belt superimposed (data from Ferguson & Gannett 1932; Clark & Lydon 1962; Clark 1992; Long *et al.* 1998; Frank 1999; Saucedo *et al.* 2000; Bankey *et al.* 2002; USGS 2002, 2006).

Sierra Foothills Gold Province, California
Bierlein et al (2008)

Common Characteristics of Large Scale Ore-Controlling Structures

Strike-extensive

Depth-extensive (lithospheric mantle) with relatively steep dips

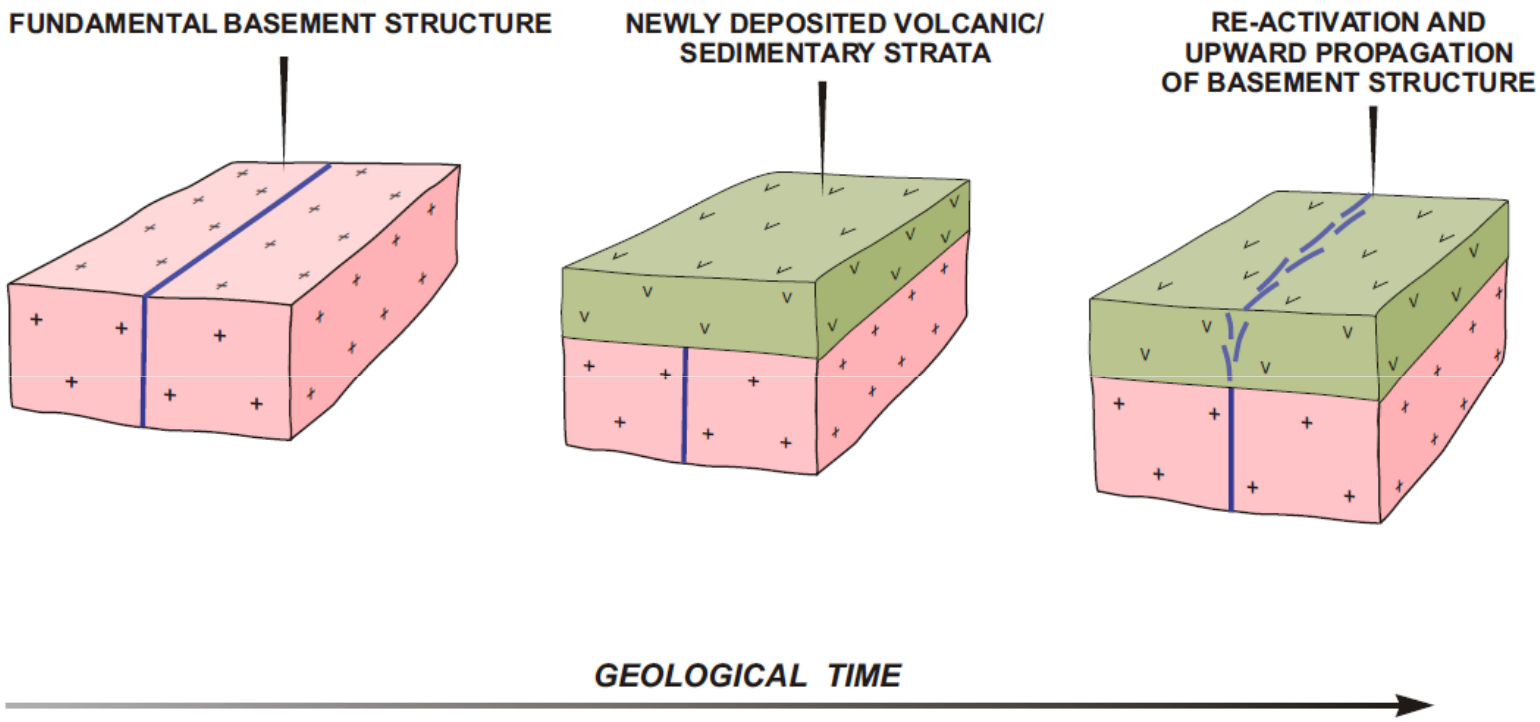
Commonly juxtapose distinctly different basement domains

Multiply-reactivated (commonly with variable senses of movement) with a *very long* history.

Vertically-accretive growth histories.

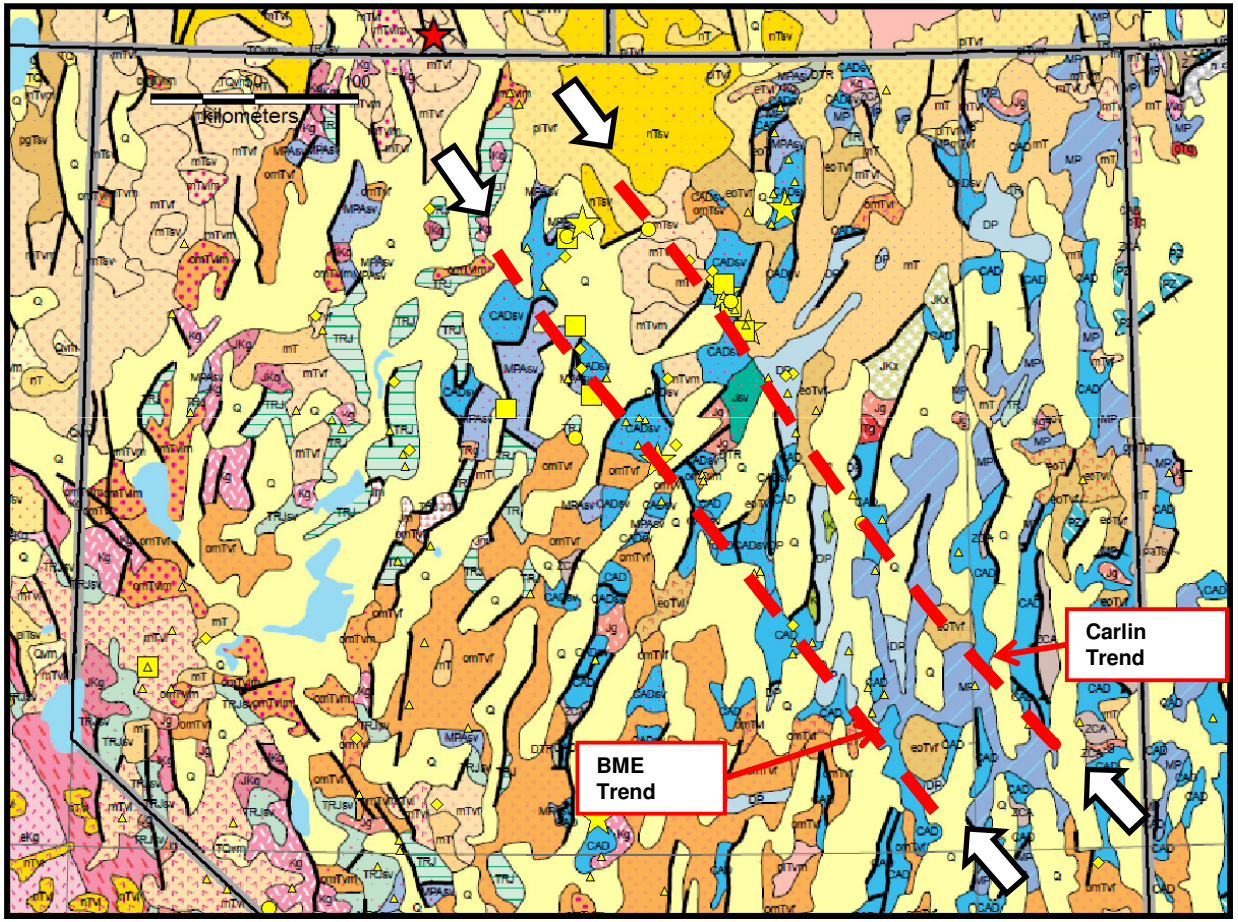
These are usually not the obvious structures at the crustal level of mineralisation – an important message for targeting

Vertical Accretive Growth History



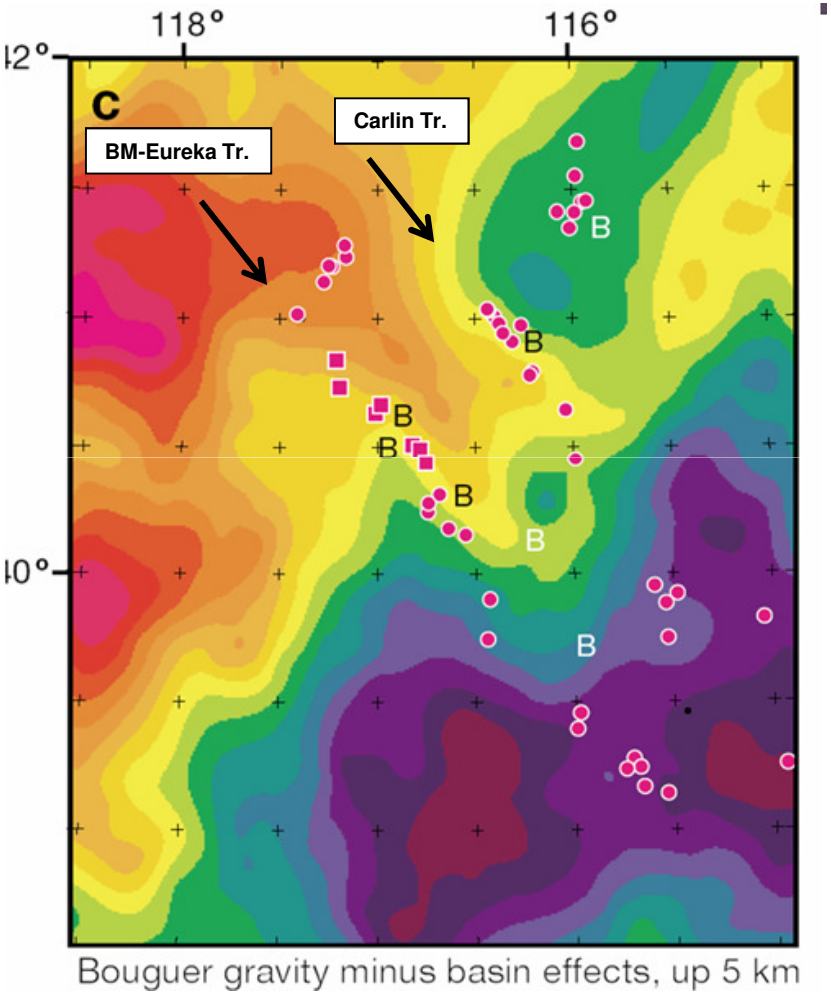
McCuaig and Hronsky (2014)

Cryptic Near-Surface Pattern Overlying Fundamental Structure at Depth



Carlin and Battle Mountain–Eureka trends *not* obvious in surface geology

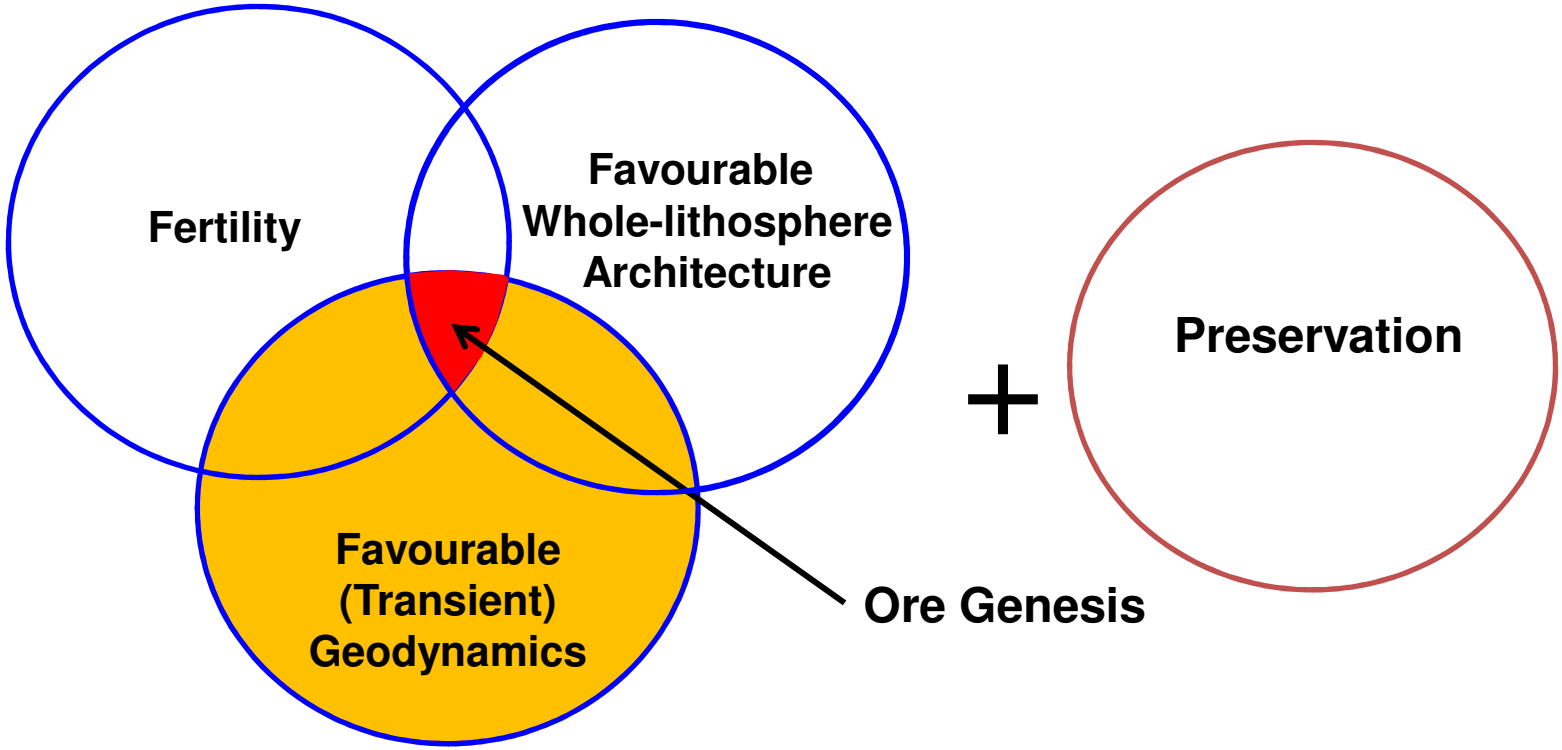
Cryptic Near-Surface Pattern Overlying Fundamental Structure at Depth



Grauch et al., 2003

Bouguer data processed to image deep architecture – trends much clearer!

Critical Elements of Mineral Systems



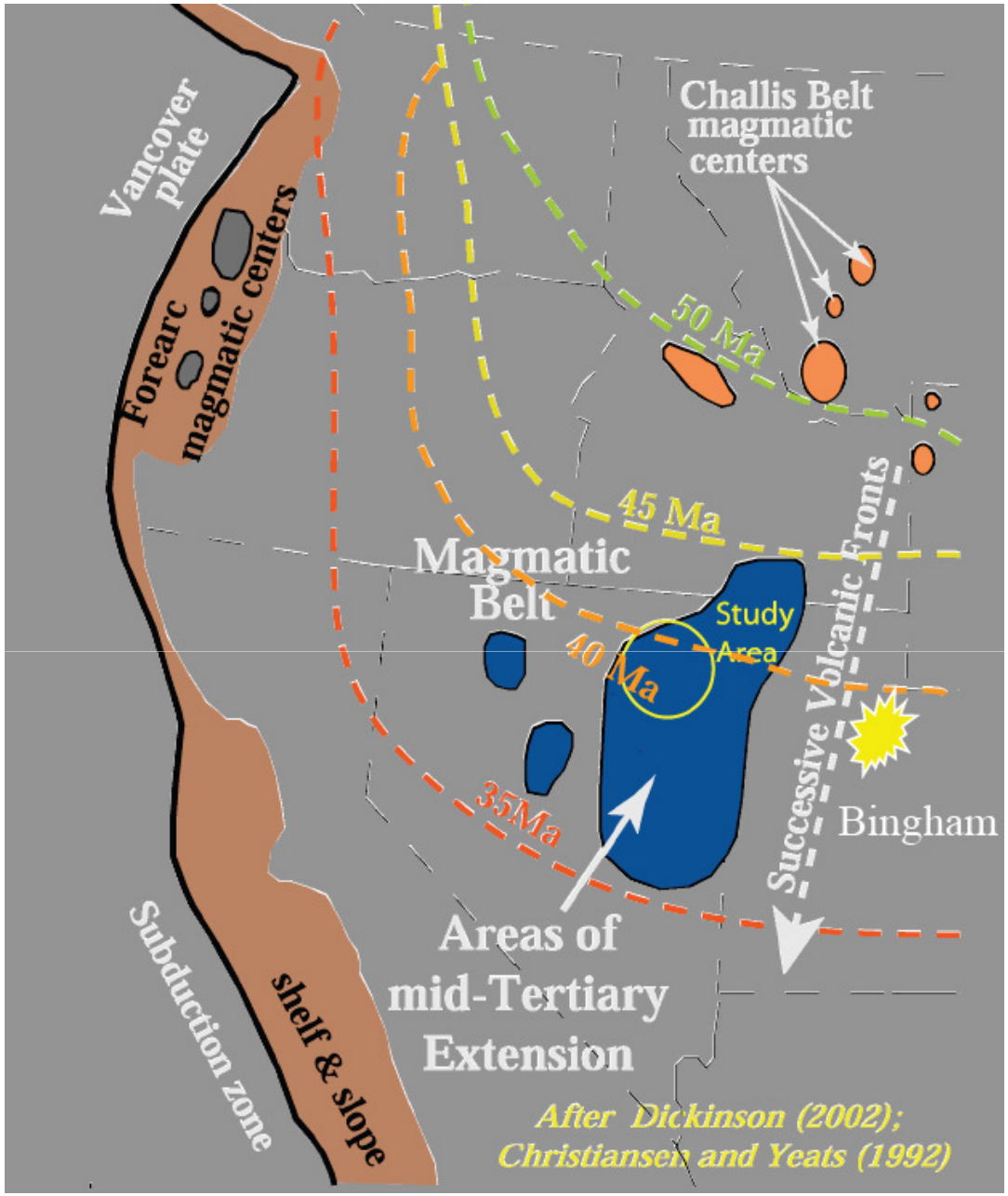
Favourable Transient Geodynamics

In recent years increasing availability of high-resolution geochronology and better understanding of global geodynamics

Tells us that major ore-forming events (*of all types!)* occur in narrow time windows, often over broad areas

These critical time horizons must reflect unusual regional-scale geodynamic settings, favourable for mineralisation

These favourable settings must be transient, lasting for only short periods of geological time



Tosdal (2009)

Eocene transition from compression to extension in SW USA

Bingham, Carlin and Cripple Creek all form associated with this event

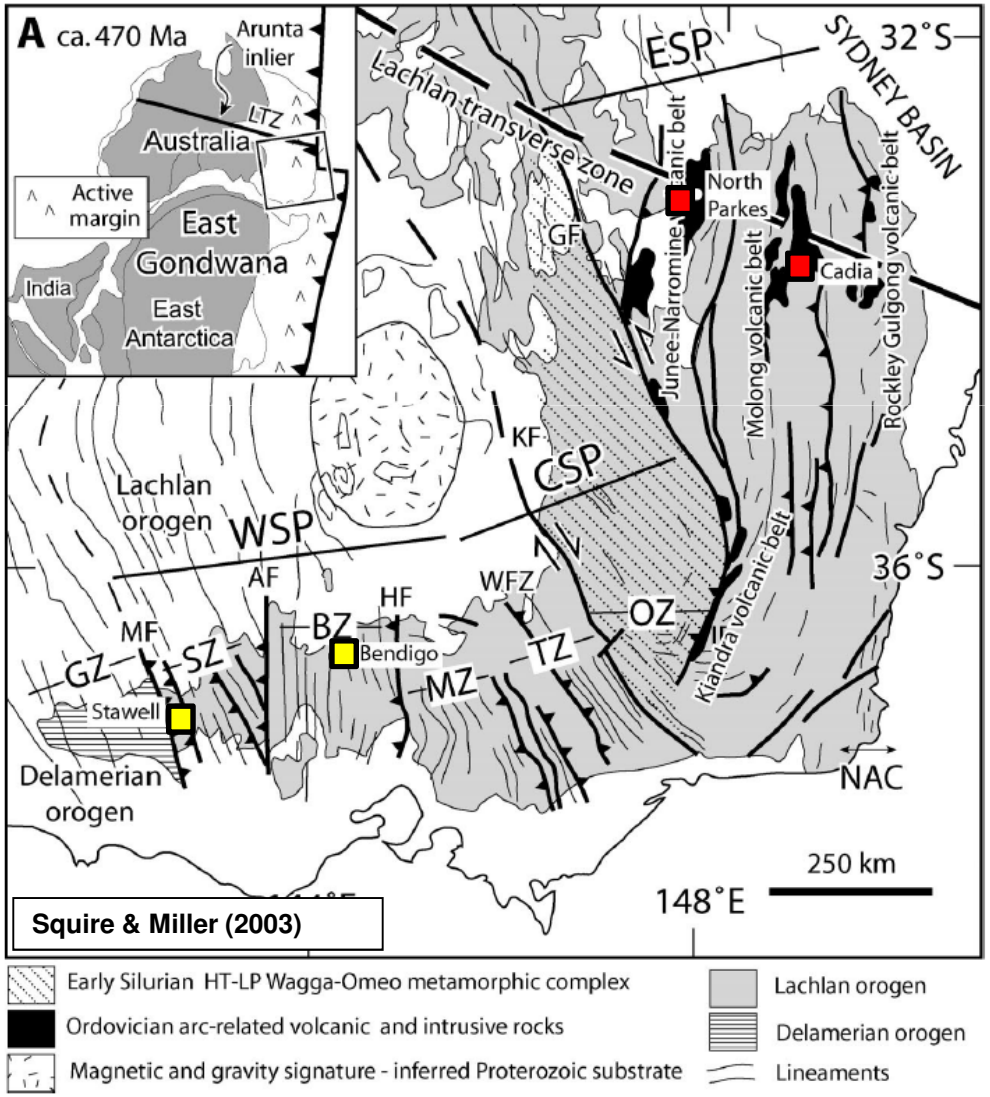
Very different deposit styles, same geodynamic trigger?

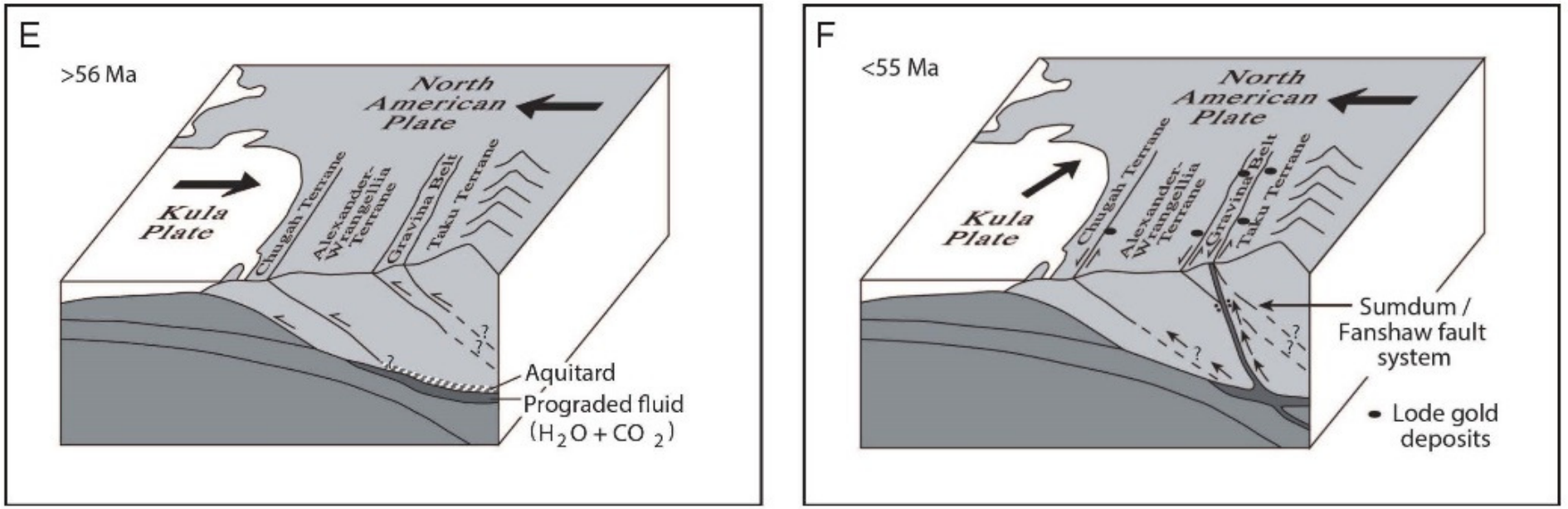
Lachlan Orogen

All these major deposits formed at c. 440 Ma

Large Orogenic Au deposit

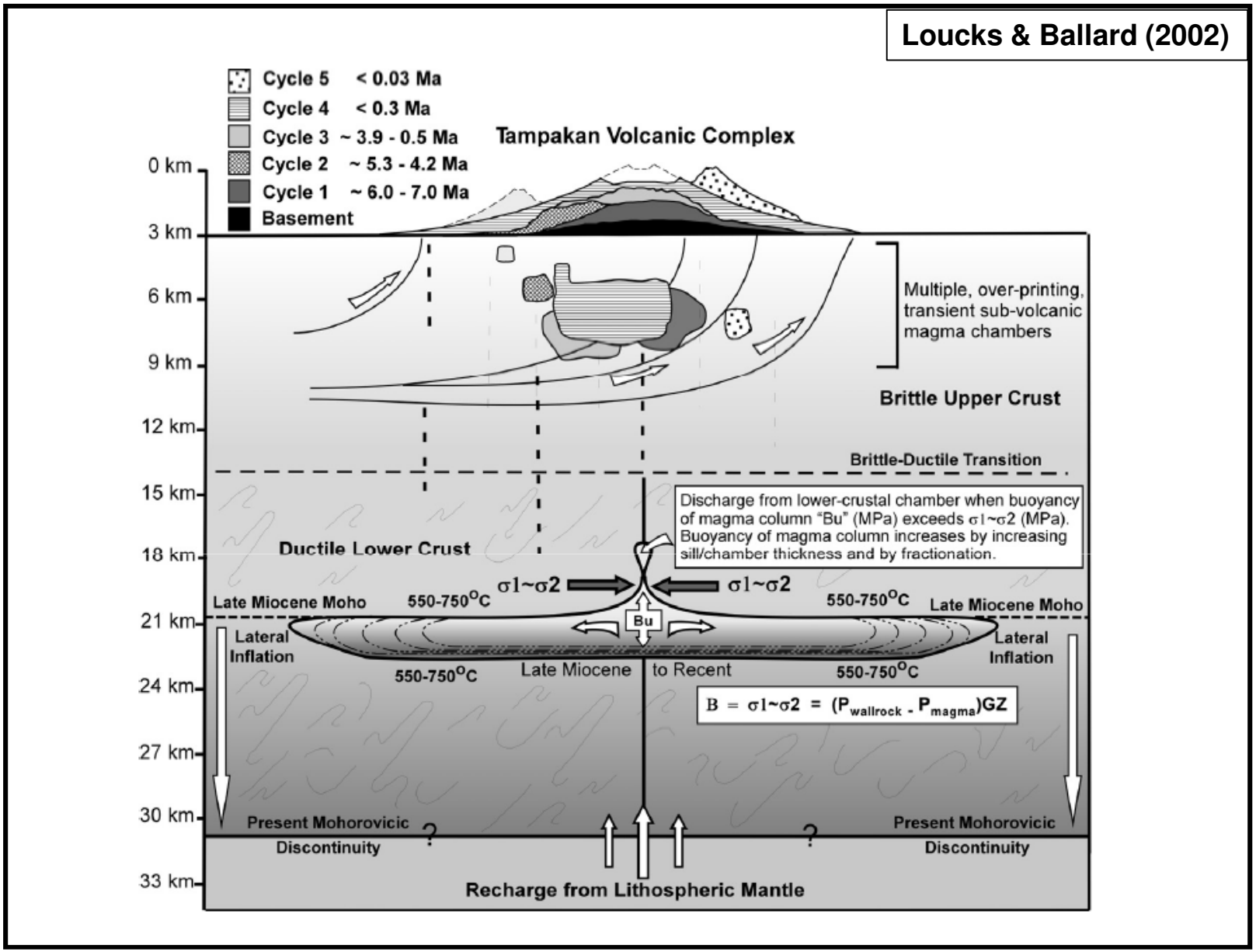
Large Porphyry Cu-Au deposit





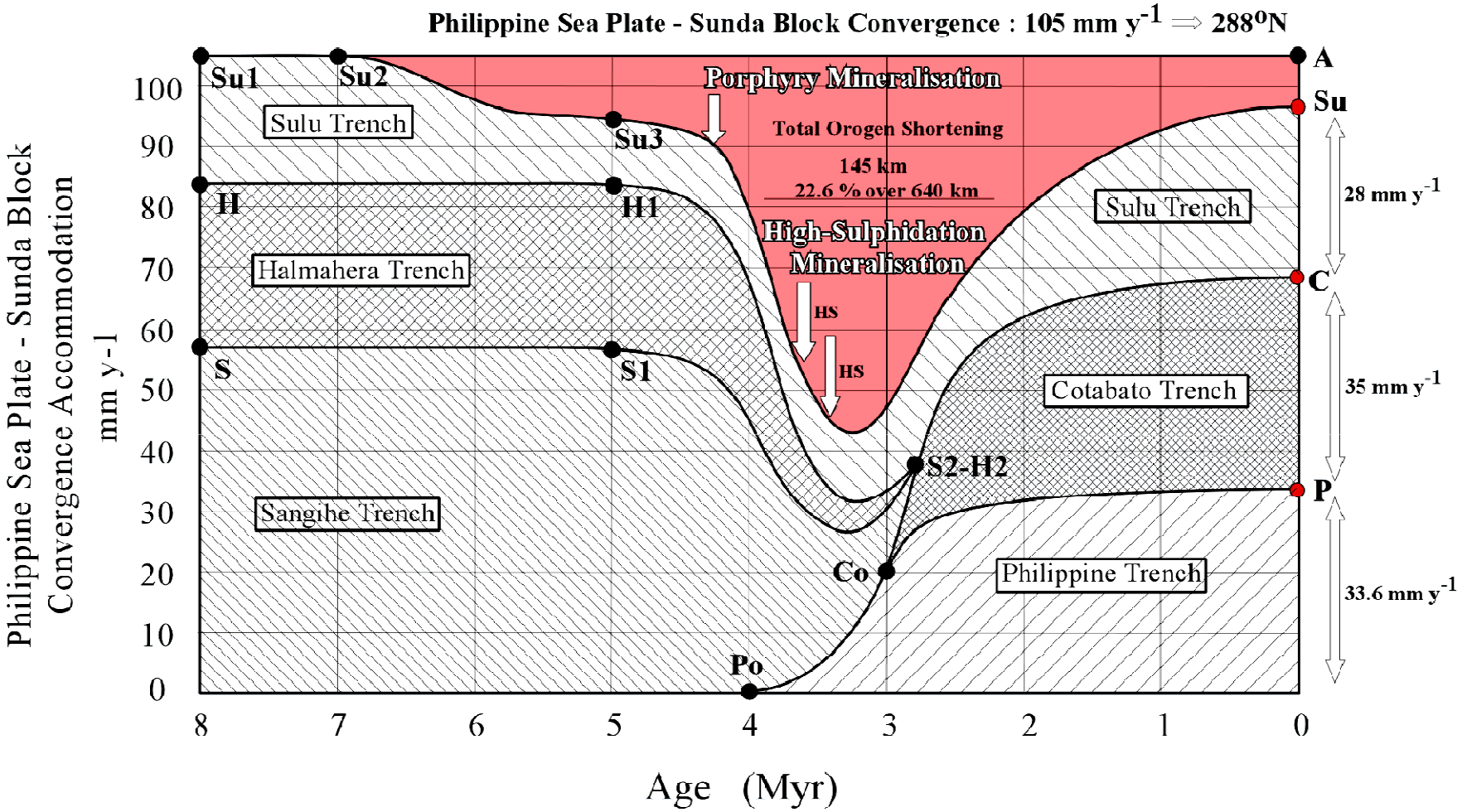
Goldfarb et al., 2005

Juneau Orogenic Gold Belt



Model for the long-lived Tampakan magmatic system (no vertical exaggeration):

A major deep-seated arc magmatic complex feeds a semi-continuous volcanic complex for about 7Ma. However, PCD/HSE mineralisation is tightly restricted in time



Red area = amount of convergence partitioned into intra-plate shortening during subduction reversal. From Rohrlach (2002)

Favourable Transient Geodynamic Events

Empirically three common scenarios:

1. Incipient Extension

(VMS, Alkalic LSE Au, LSE Au, NiS)

2. Transient Anomalous Compression

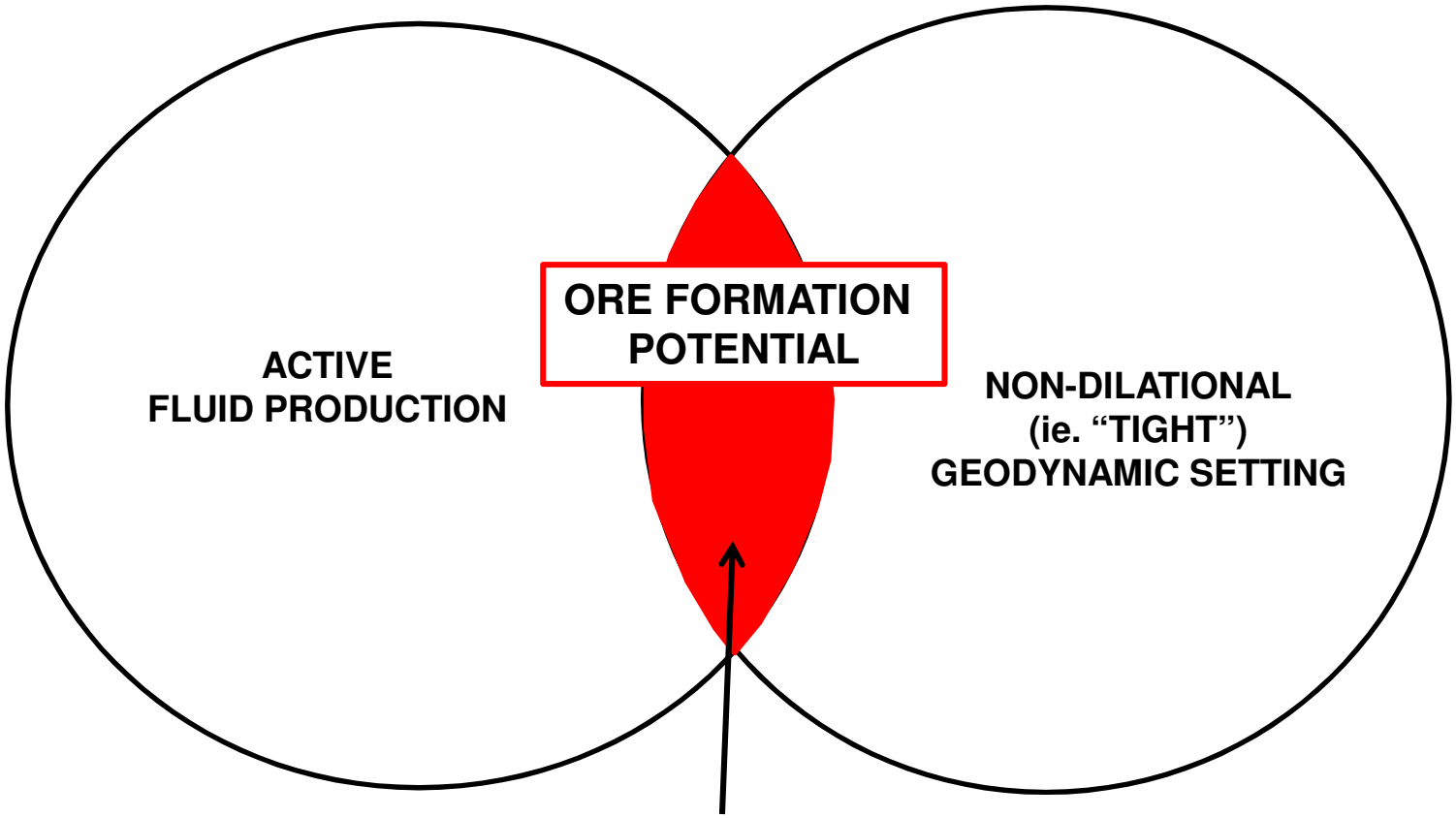
(Porphyry Suite deposits, Mafic Intrusion NiS?)

3. Switches in Far-Field Stress -transiently neutral stress field

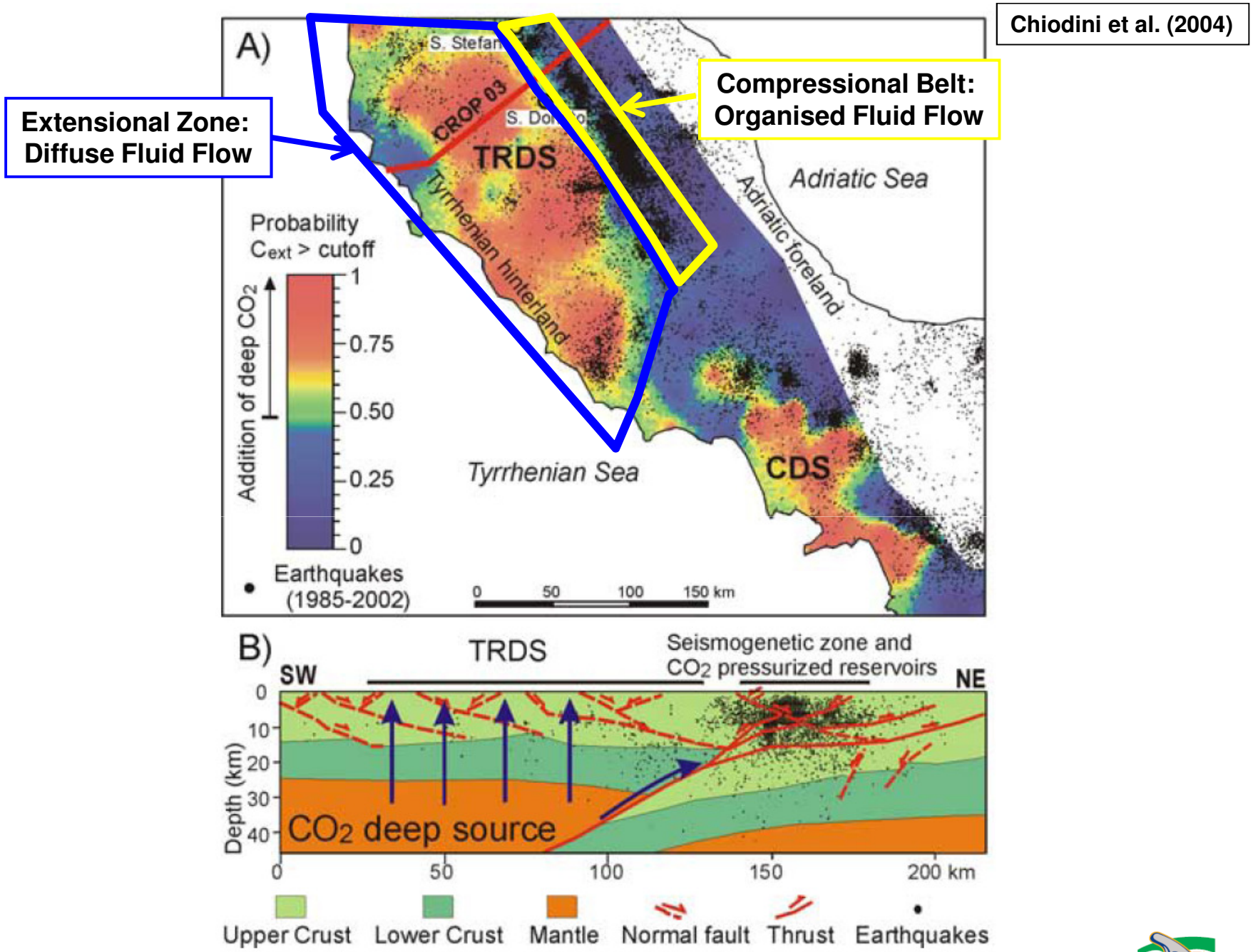
(D.Tosdal; Pers. Comm)

(All?)

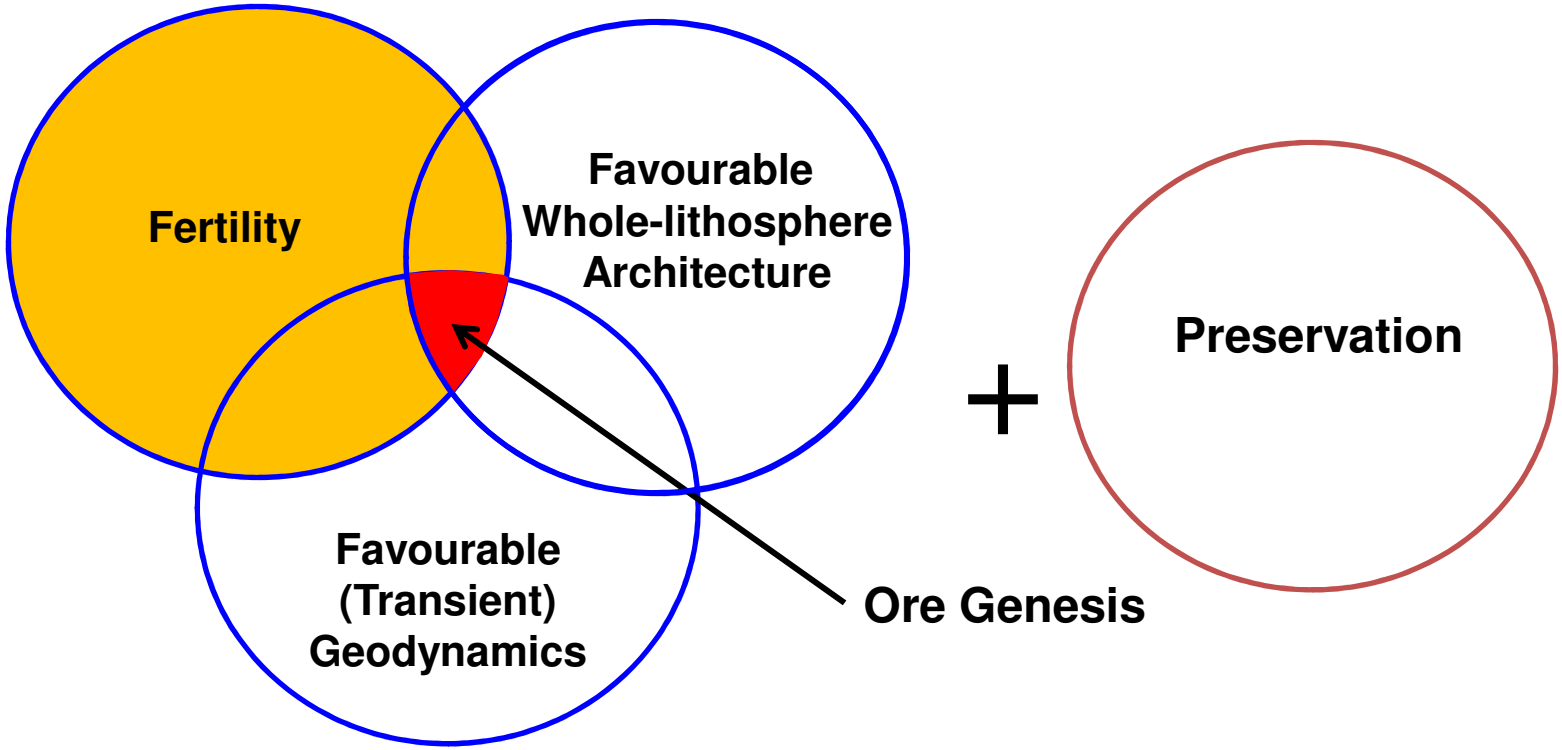
Favourable Transient Geodynamic Events – Why?



Chiodini et al. (2004)



Critical Elements of Mineral Systems



Fertility

A geological region or time period systematically better-endowed than otherwise equivalent geological environments

4 components

- **Secular Earth Evolution**
- **Lithosphere fertility (e.g. Au)**
- **Geodynamic context (e.g. magmatic-hydrothermal Cu)**
- **Paleolatitude (Zn-Pb, U, Fe, others?)**

Fertility - Secular Earth Evolution

1. **Cooling of earth through time**

   e.g. Komatiite-hosted NiS

2. **Evolution of biosphere-atmosphere-hydrosphere**

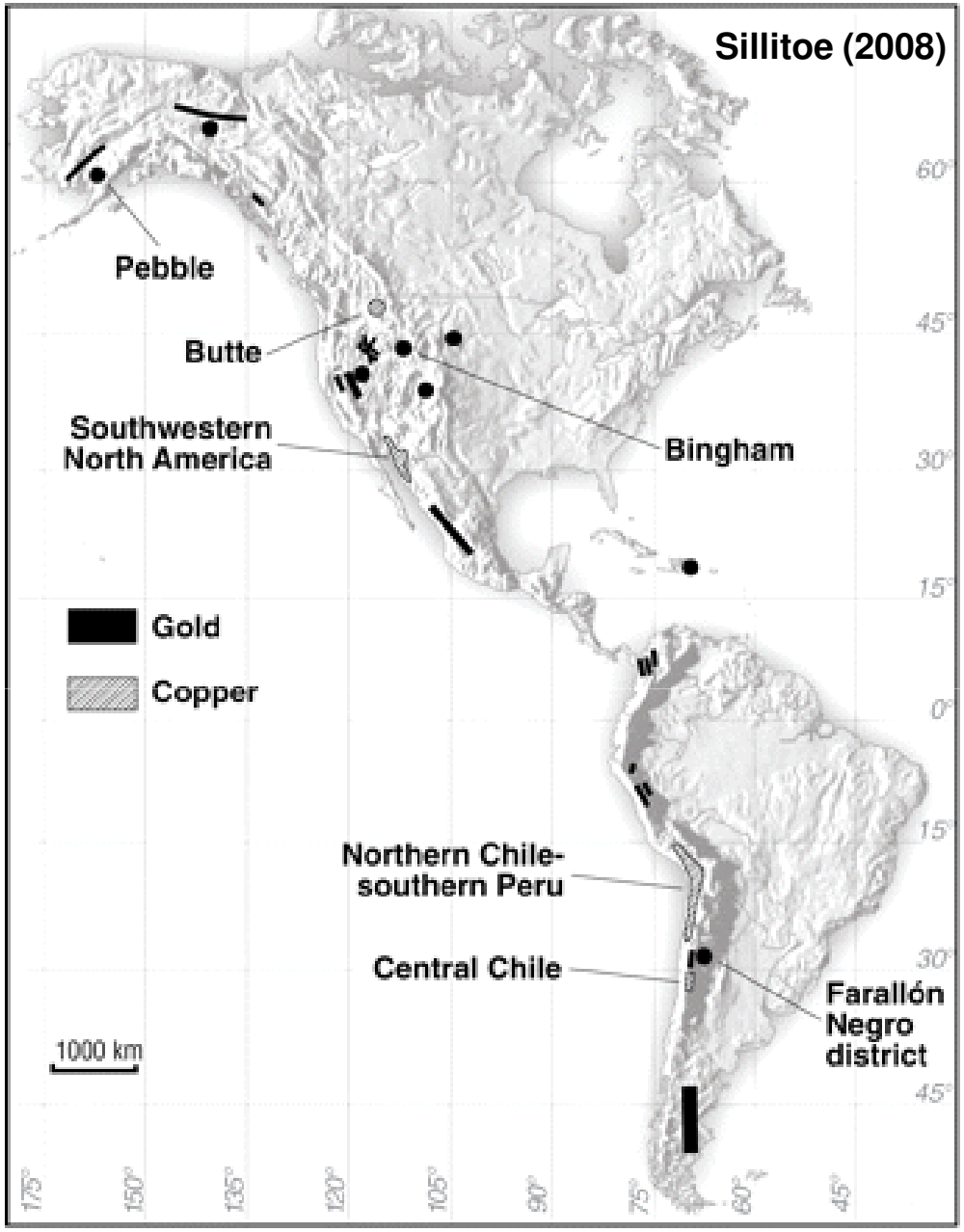
   Controls availability or mobility of metals

   e.g. U, sediment hosted Pb-Zn

3. **Evolution of lithosphere and geodynamic cycles**

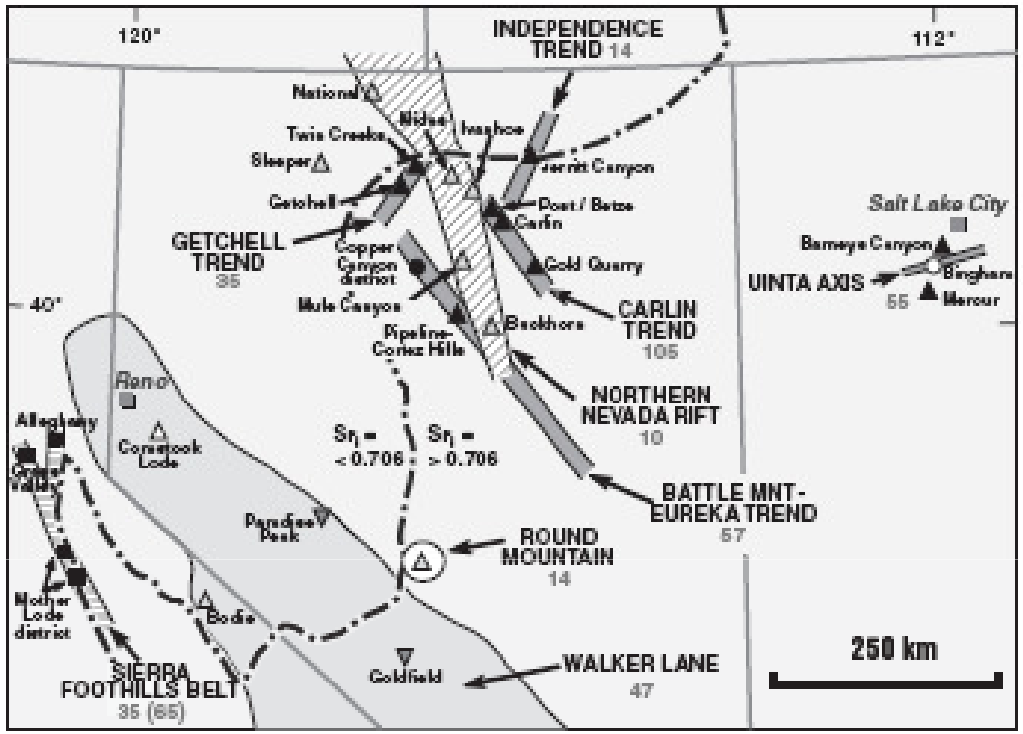
   e.g. Orogenic Au at terminal stages of supercontinent assembly

   The first time a favourable chemical system encounters a favourable geodynamic environment may be particularly fertile! (eg Unconformity U)



Fertility – Lithosphere Enrichment

Sillitoe (2008)



Metallogenic Belt Age

- Early Cretaceous
- Eocene
- Oligocene (26 Ma)
- Miocene (20 – 4 Ma)
- Miocene (16 – 14 Ma)

Deposit Type

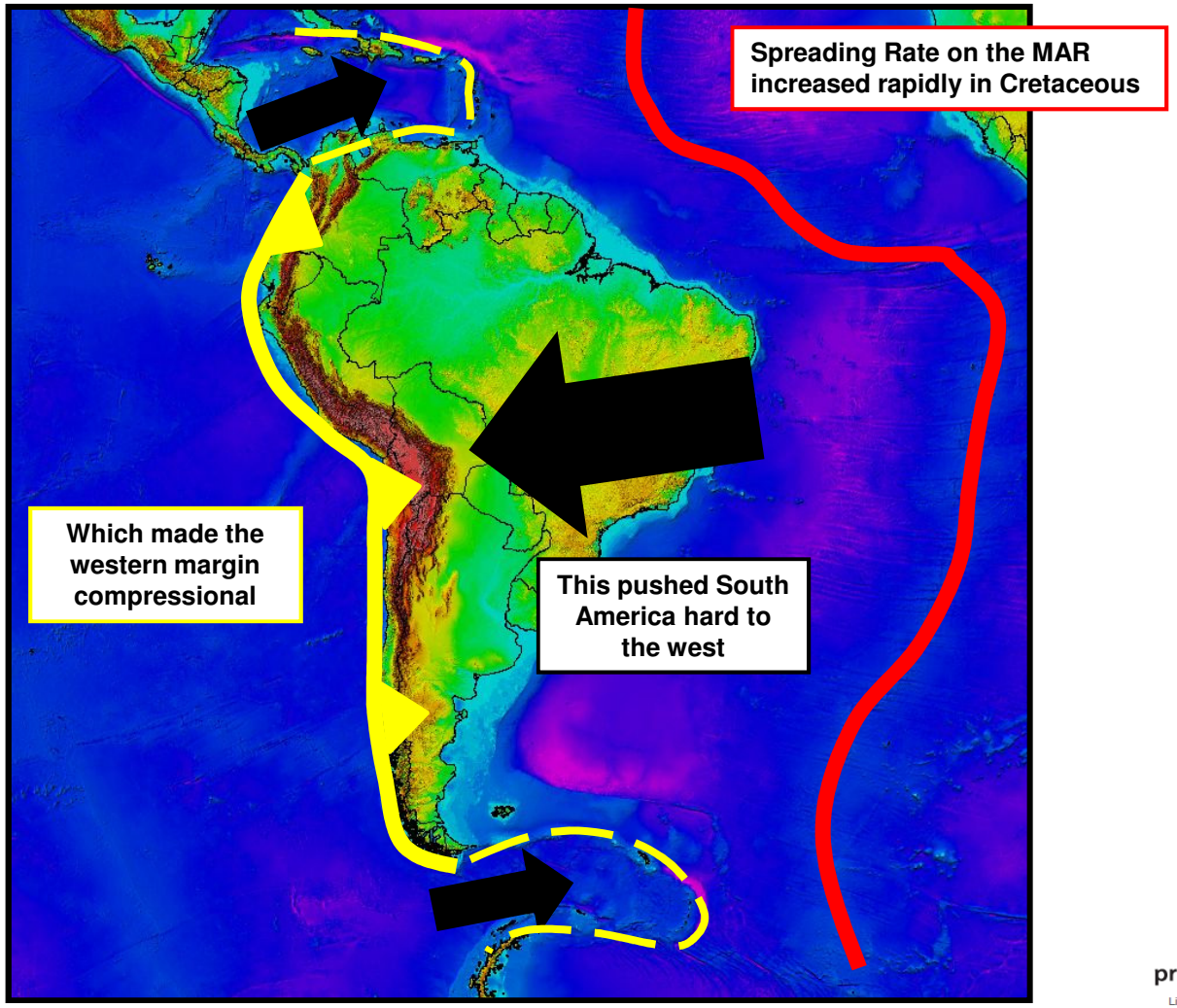
- ○ Porphyry Cu-Au
- ● Skarn
- ▲ Sediment-hosted Au
- ■ Orogenic Au
- △ Low-sulfidation Au
- △ Intermediate-sulfidation Au-Ag
- ▽ High-sulfidation Au ± Ag

FIG. 3. Major gold belts and isolated major deposits in the Great Basin and surrounding regions of the western United States, showing their ages and gold contents (numbers beneath belt names). The number in parenthesis is placer gold content. Several important deposits in each belt, assigned to deposit types, are also marked. Data from multiple sources, including Table 2 and references therein. Dot-dash line shows the initial $^{87}Sr/^{86}Sr = 0.706$ isopleth (Sr_i) for Meso-Cenozoic plutonic rocks (after Kistler, 1991), which is inferred to mark the western craton margin. Inset marks the position of the Great Basin physiographic provinces, mentioned in the text

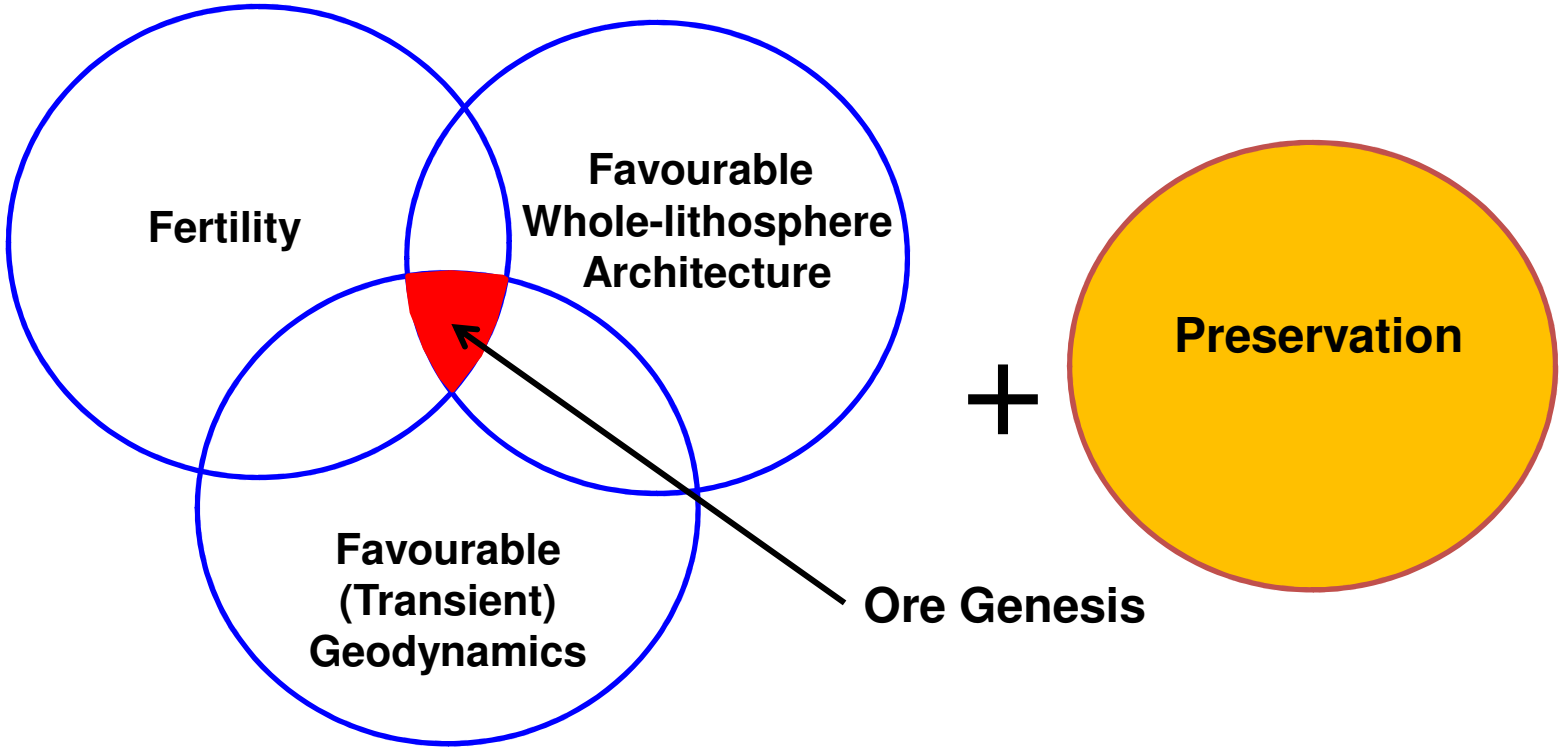
Western US Zone of Anomalous Gold Endowment: Multiple Events – Multiple Deposit Types

Fertility - Geodynamic Context

Andean Cu since the Cretaceous – anomalously compressive margin

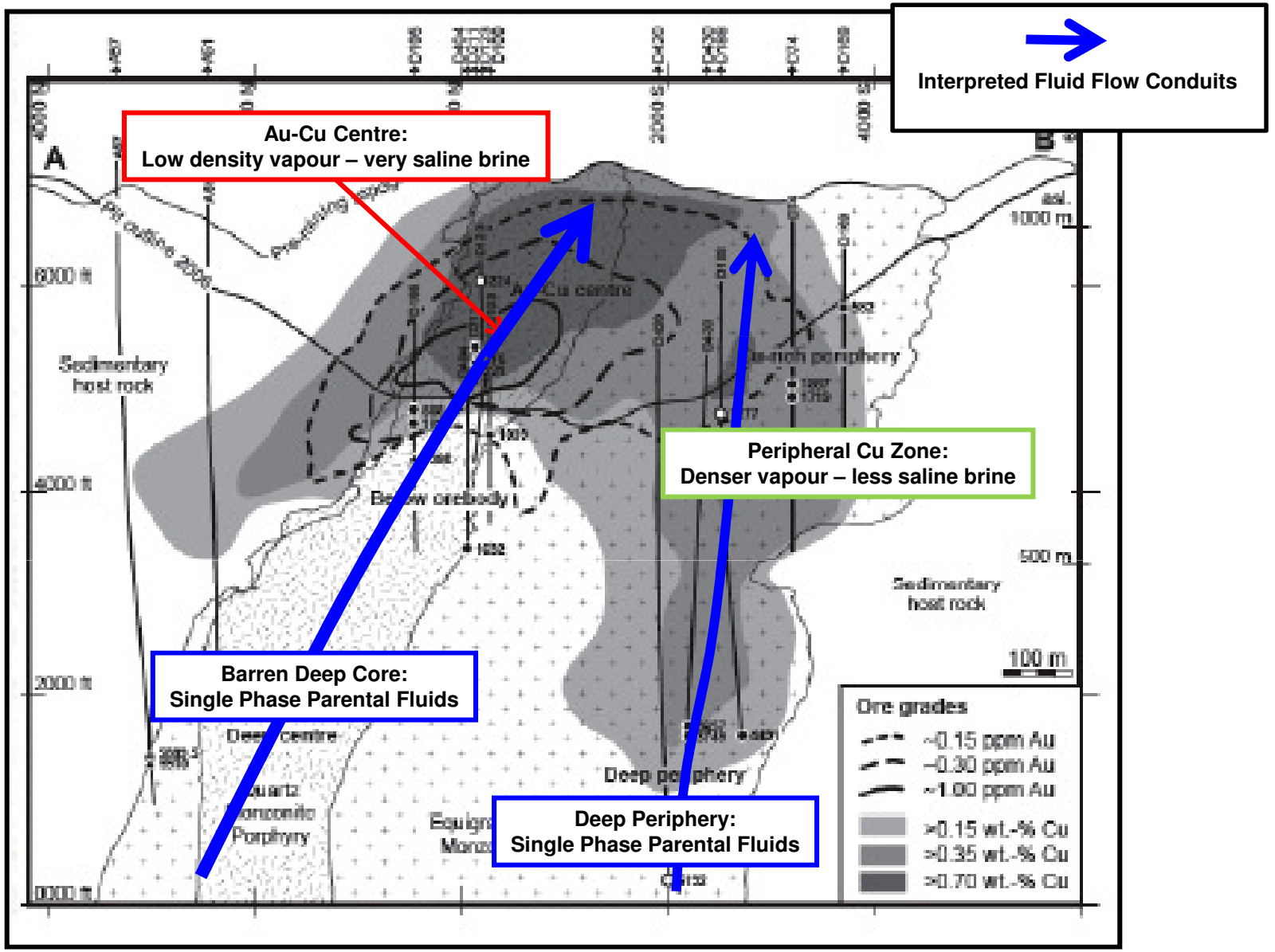


Critical Elements of Mineral Systems



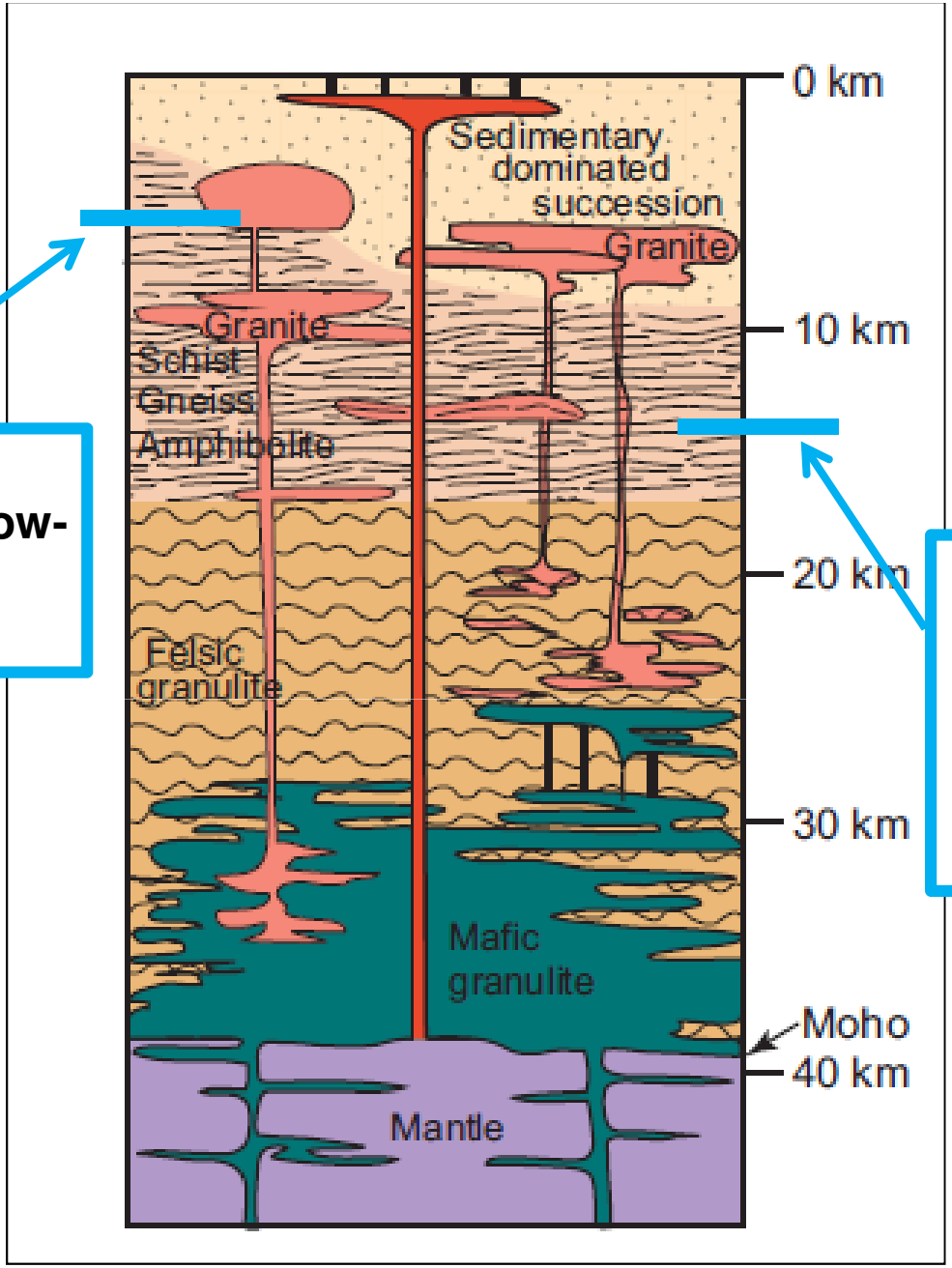
Preservation

- Globally, strong correlation between preserved *supracrustal* rocks and metal deposits - key proxy for post-mineral erosional history
- Upper crust is zone of steepest geochemical gradients
- In particular, fluid depressurisation critical in hydrothermal Cu-Au deposits
- Therefore, terranes eroded deeper than 10-15 km will usually not preserve deposits
- "Metal Depositional Window" concept – the upper 10-15 km of crustal section *during the ore-forming orogenic cycle*
- Analogous to concept of a "Petroleum window" in oil exploration, which must be preserved for a basin to be prospective



Bingham Canyon:
Controls on Cu/Au deposition related to unmixing of an ascending ore fluid
(Landtwing et al, 2009)

Base of Metal Depositional Window- Porphyry Style deposits



Base of Metal Depositional Window- Orogenic Gold deposits (more CO_2-rich fluids)

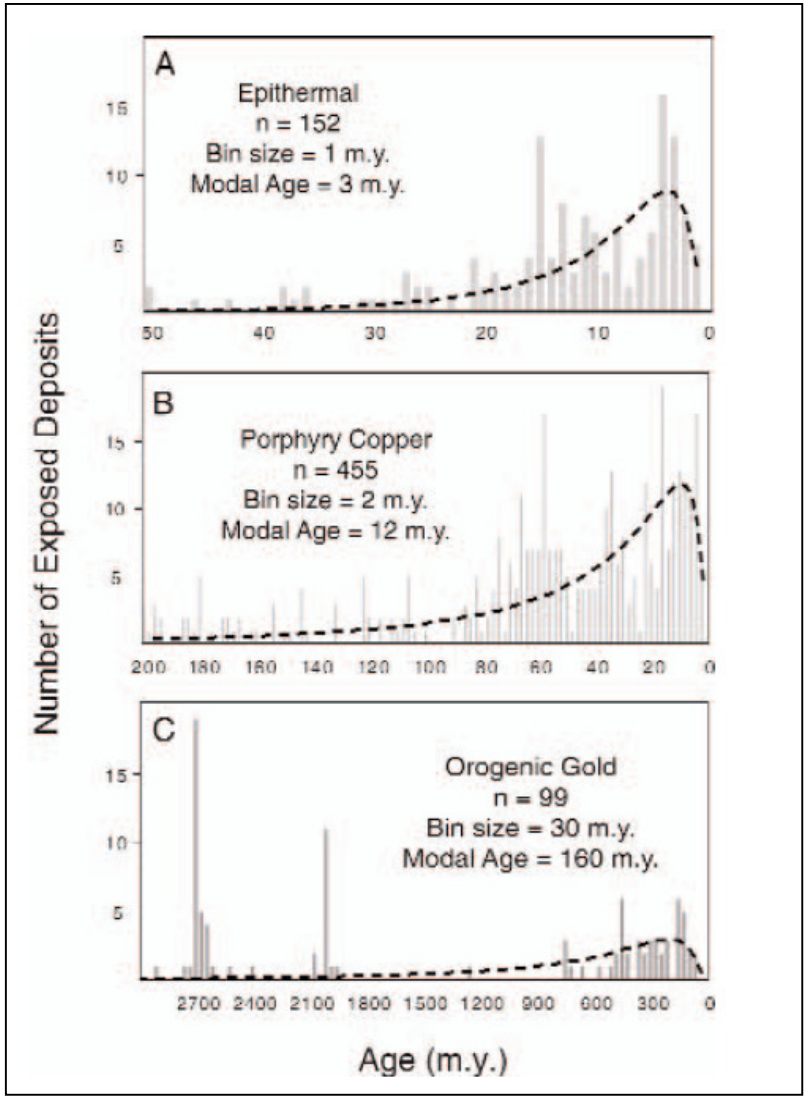
Schematic Section - Continental Crust

(Cawood et al, 2013)

Deposit Type and Preservation

- Preservation varies between different deposit classes
  - Most Porphyries Cenozoic, whereas Orogenic gold and VMS are present throughout geological time

- Host Geodynamic setting an important control



Dashed lines = progressive erosion model; Kesler & Wilkinson (2006)

Progressive Erosion Model :

Explains observed distribution of Epithermal and Porphyry deposits well but not Orogenic deposits

Metallogenic Association	Typical Deposit Types	Emplacement Environment	Long Term Preservational Potential
1	Porphyry-suite deposits	Compressional Arcs	Low – typically very high uplift and erosion
2	Rift associated Epithermal, VMS	Rifted Arcs; shallow rifts for Epithermal, deep submarine rifts for VMS	Low for Epithermals in shallow rifts; Moderate for VMS in deeper rifts
3	Orogenic Au	Deep in Inverted Back-Arc Rift, Very Late timing	High - limited post-ore uplift and erosion
4	Olympic Dam style IOCG Sleeper style Epithermal	Intracontinental rifts or anorogenic sites	High *if* emplaced post-cratonisation Moderate if emplaced during the orogenic cycle

Summary of the Preservational Potential of Major Au(Cu) deposit types

Metallogenic Association framework derived from Hronsky et al (2012); Note that all deposits are susceptible to removal by subsequent unrelated orogenic cycles

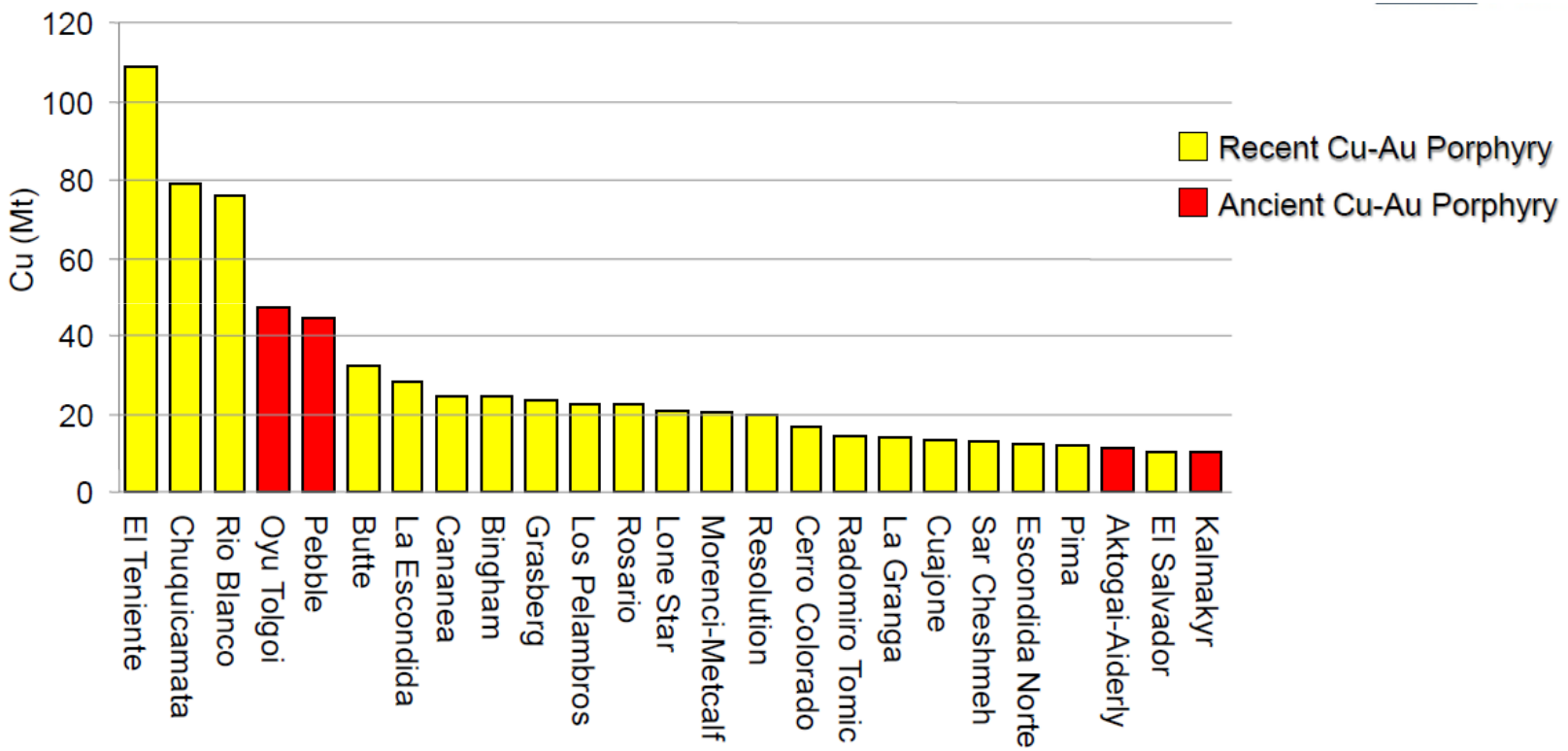
Preservational Potential of Porphyry Deposits

- Most Porphyries are Cenozoic because they form in areas of high uplift and erosion
- Significantly, older deposits tend to occur as isolated giants (eg Oyu Tolgoi, Cadia) whereas younger deposits typically occur in belts of multiple deposits
- Older deposits require anomalous post-ore subsidence for their preservation
- Because localised subsidence may be controlled by the same type of major structural intersection that controls ore localisation, this may be *more likely* at the sites of giant deposits

El Teniente

Grasberg

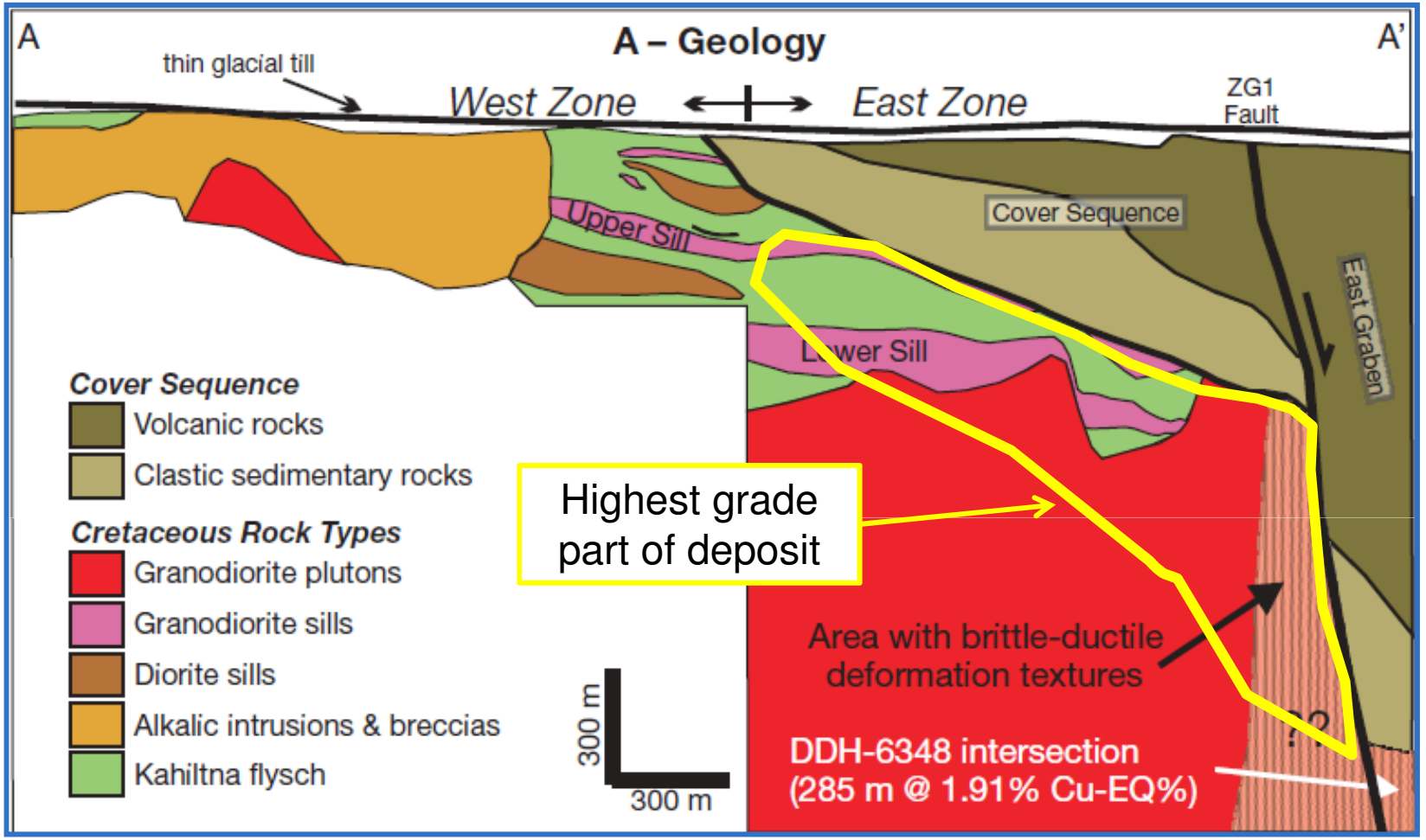
Although Older Porphyries are Rare they include some Giants



Wurst (2010)

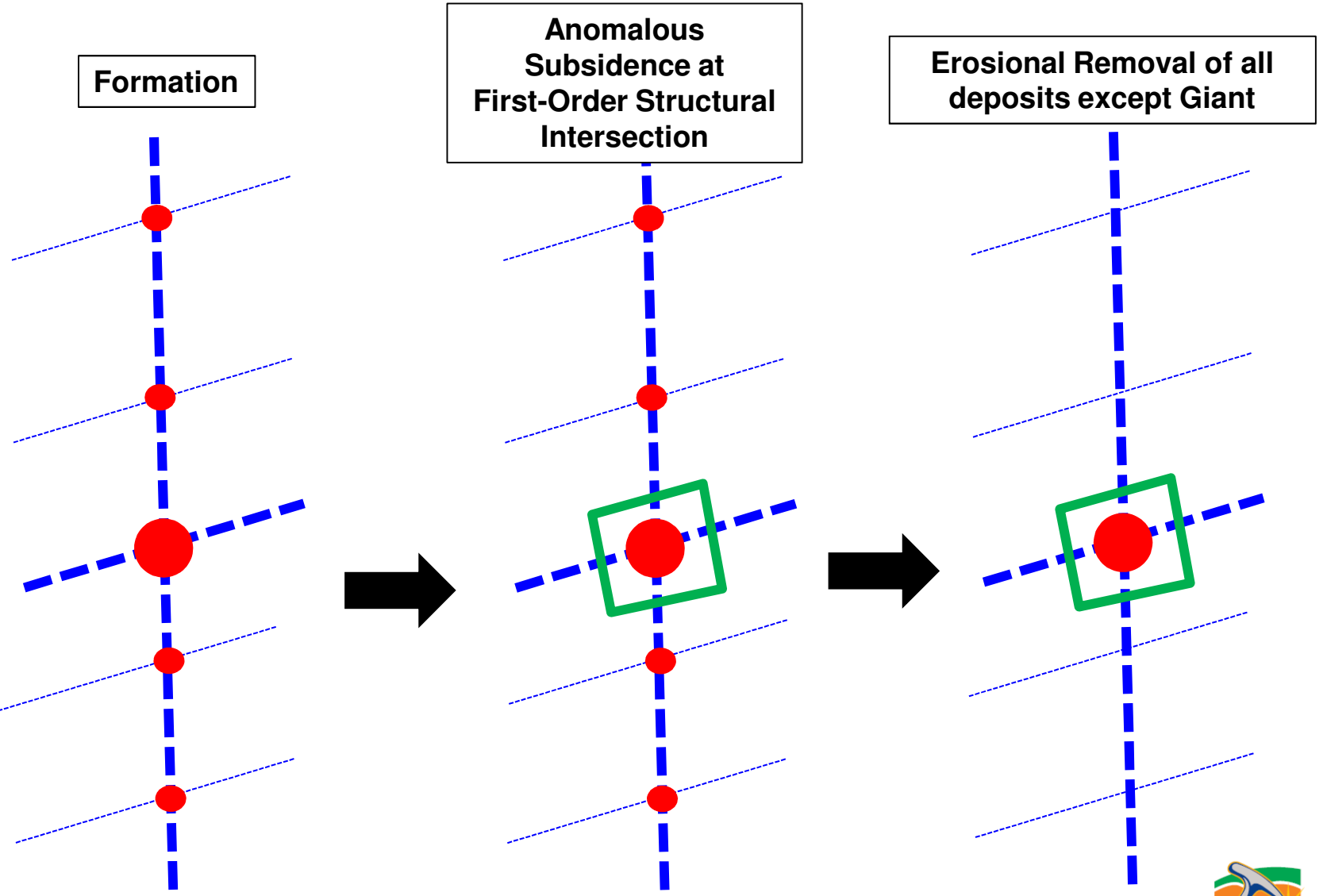
ter Cooke et al. 2005

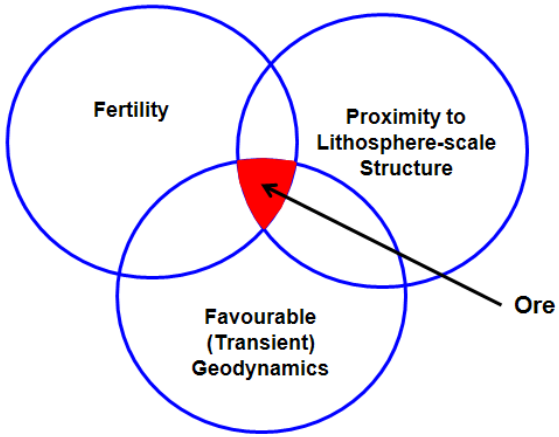
Lang et al (2013)



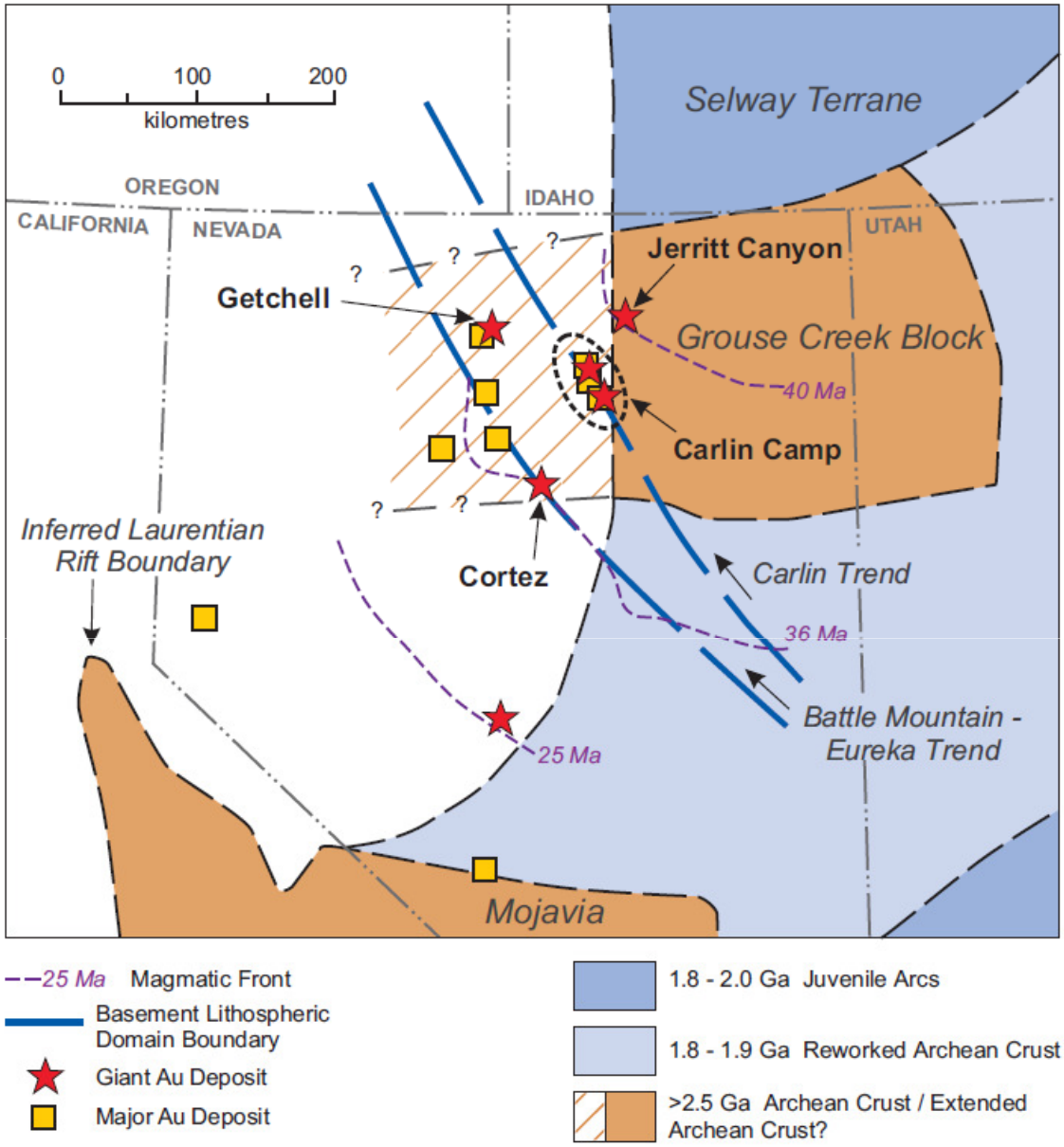
Pebble – good example of the major ore-controlling structure also controlling later subsidence which helps preserve the deposit

Model:
Selective Preservation of Giant Porphyry Complexes





Putting it together - Carlin Gold Example



(Hronsky et al 2012; Modified after Whitmeyer & Karlstrom 20 Muntean et al, 2011)

TABLE 1. Critical and Constituent Elements in the Formation of Gold Deposits[1]

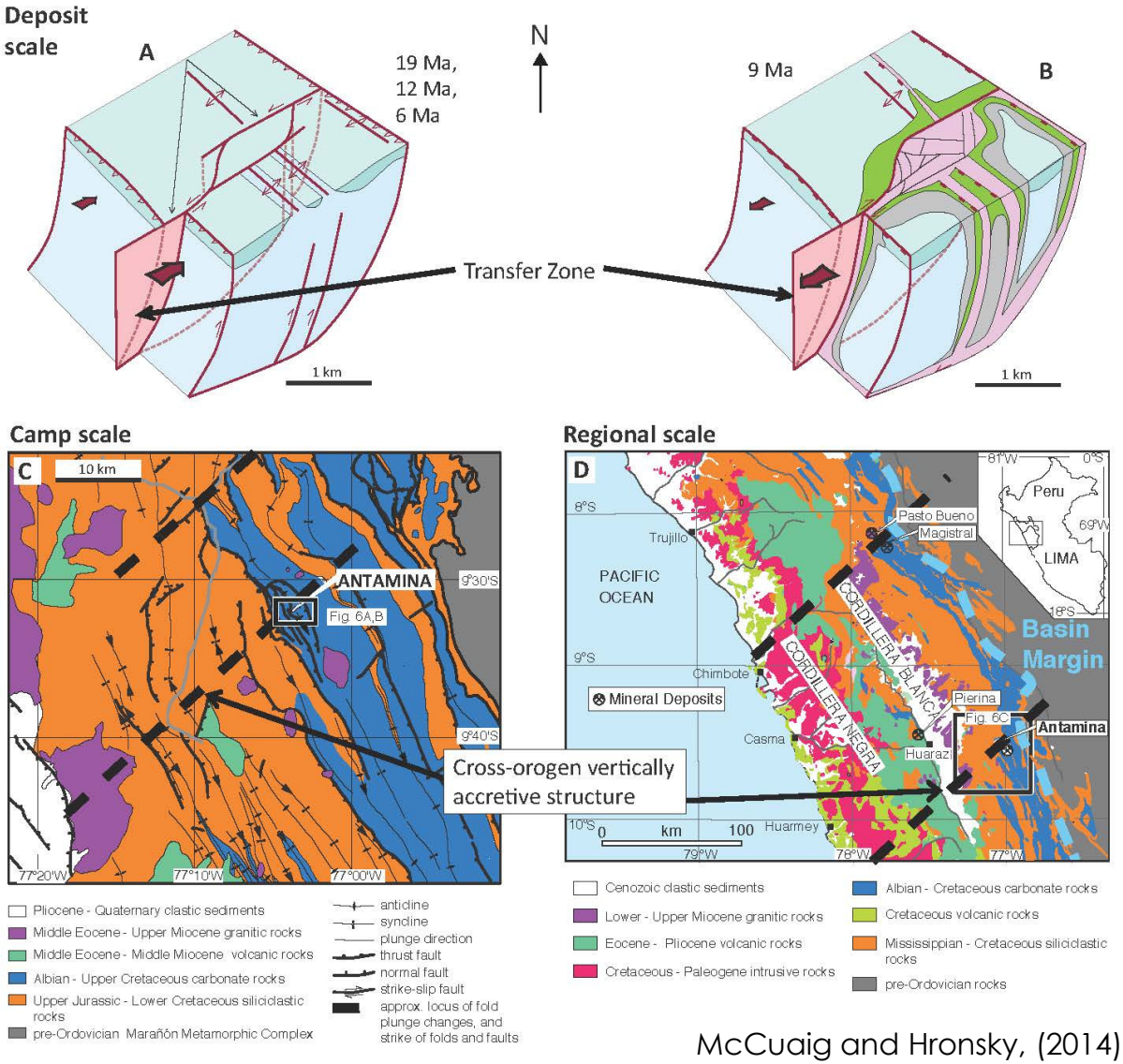
Scale	Critical elements: Fertility	Favorable geodynamics	Favorable architecture	Primary depositional zone
Ore-shoot	N/A at this scale	N/A at this scale	Localized dilatant zone in conduit-hosting structure	2nd order—pressure drops; 3rd order—favorable substrate (chemical reaction)
Deposit	N/A at this scale		Pipelike rock volume more favorable for fracturing by fluid-exit pulse (either local structural complexity or pipe of more competent rock)	
Camp	N/A at this scale	Period of low active tectonic strain, e.g., stress switch causing transient neutral stress state causing fluid system to self-organize; areas of greatest uplift favored (provides stress switch and high rates of energy and mass transfer)	Major heterogeneity (e.g., cross-structure intersection) along trend of inverted rift-axial (or rift-marginal) fault with associated physical seal (e.g., antiformal culmination or unconformity)	1st order—upper 10 km of crust *at the time of mineralizing event* where fluid pressure (+T, X) gradients are greatest; preserved through multiple orogenic cycles
Province	Discrete Au-enriched upper lithospheric domain, particularly near its margins; potentially mantle lithosphere enriched by small volume partial melts prior to termination of orogeny	Terminal phase of synore orogenic event (e.g., the transition to incipient extension associated with the termination of collision and locus of subduction retreating oceanward)	Inverted retroarc rift; preferably developed at a continental margin, or margin of deep mantle lithosphere root; long-lived "vertically accretive" structure	
Continental	Currently unclear but the occurrence of the western US gold superprovince suggests that some control at this scale exists	A major collisional orogenic event within the history of an evolving accretional orogen; the major collision that actually terminates a long-lived (>200 Ma) accretionary orogen is most prospective and usually associated with a peak of supercontinent formation	Major subcontinental scale lineament (representing long-lived zone of transverse dislocation within accretionary orogen); long-lived "vertically accretive" structure	

Notes: Note the scale-dependent nature of the constituent elements; these elements require translation into features that can be mapped directly in existing or obtainable geoscience datasets at the appropriate scale to generate targets (e.g., McCuaig et al, 2010)

How We Summarise a Mineral System Model:
Orogenic Gold Example

McCuaig & Hronsky (2014)

Multiple Scales of Structural Control – Antamina



McCuaig and Hronsky, (2014)

Key Messages

- **Predictive targeting requires an organising framework – the Mineral System approach**
- **Ore deposits are part of a much larger system**
- **Ore-forming systems show diverse chemical processes but a much narrower range of *physical* processes – focusing on these is the key to predictability**
- **Mineral systems are complex dynamic systems, exhibiting self-organised critical (SOC) behaviour**
- **Critical elements of mineral systems are whole lithosphere architecture, transient favourable geodynamics, fertility, and preservation**
- **Mineral systems have different expressions at different scales**