Science, the 5 Questions and Exploration

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Mineral Systems Work Flow

The *Why* Question

Why is the orebody ***there***?

5 Questions

1. Geodynamics
2. Architecture
3. Fluid reservoirs
4. Flow drivers & pathways
5. Deposition

Inputs from:
Data Compilation
Data Collection
Modelling

The *Where* Question

Where is the ***next*** orebody?

The 5 Questions

1. What are the geodynamic and P-T histories?
2. What is the architecture of the system?
3. What are the fluid reservoirs?
4. What are the fluid flow drivers and pathways?
5. What are the metal and sulphur transport and depositional processes?

Developed from inspiration provided by Tom Loutit by (amongst others) John Walshe, Alison Ord, Bruce Hobbs & Greg Hall in the AGCRC 1997-98

How do the 5Q help?

- Mineral System focus
- Away from Source - Transport –Trap
  - Ignores geodynamic and geological context, mixes fluid, metal (and sulphur) sources, implicitly links fluid flow drivers and pathways and finishes with erroneous concept of traps
- Integrated framework for understanding ore deposits
- Concentrate on processes (not deposits)
- Provide the framework for a systematic approach to analysing prospectivity and exploration risk

Talk Outline

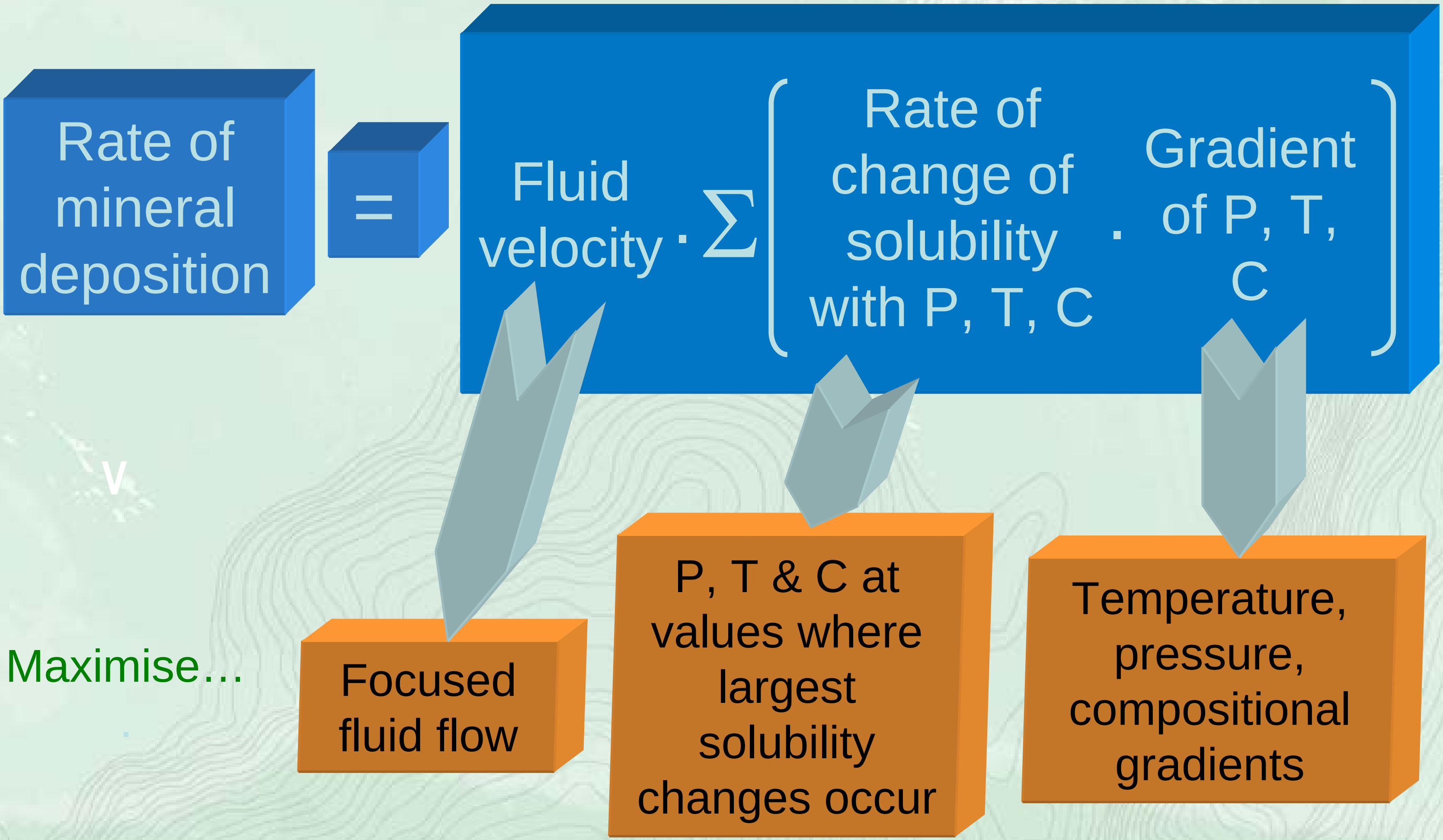
- **Why do giant ore deposits form?**
  - **Phenomenological approach**
- **A set of 5 necessary, sufficient and independent factors**
- **Fluids in Mineral Systems**
- **The 5 factors**
- **Implications:**
  - **Exploration risk analysis**
  - **Research and numerical simulation**

Why Do Giant Ore Deposits Form?

….because a lot of the appropriate mineral(s) precipitate

So what controls mineral precipitation?

Fundamental Relationship



Maximise…

After Phillips, 1990, 1991

Two Additional Relationships

$$\text{Fluid velocity} = \frac{k\rho g}{\mu} \cdot \text{Gradient in hydraulic potential}$$

$$\text{Total quantity of mineral deposited} = \int \text{Rate of Mineral Deposition} \cdot dt$$

So…….

Quantity of Ore is a function of:

A. Gradient in hydraulic potential
B. Time
C. Permeability
D. Solubility sensitivity with P, T, C
E. Spatial gradient of P, T, C

5 Questions

- Geodynamics
- Architecture
- Reservoirs
- Flow paths & drivers
- Deposition

The Largest Ore Deposits Form...

When and where

- **Gradient in hydraulic potential**
- **Permeability**
- **Solubility sensitivity to P, T, C**
- **Spatial gradient of P, T, C**

have all been maximised over prolonged period of time

Drivers; Geodynamics

Pathways; Architecture

Deposition; Architecture; Geodynamics

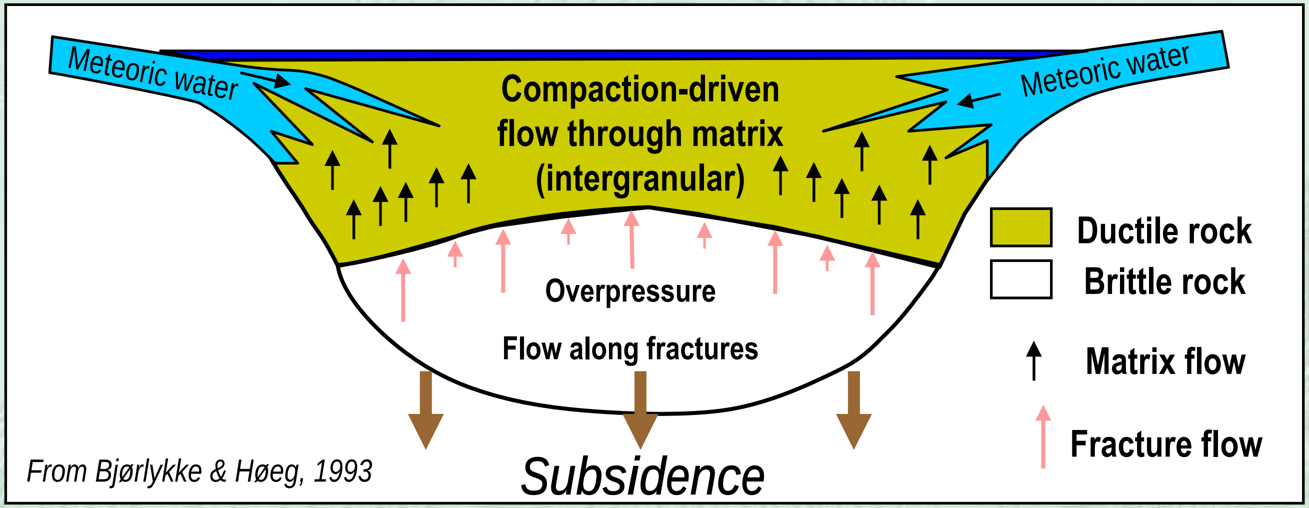
Architecture, Drivers, Deposition

Geodynamics

Fluid Sources: 1

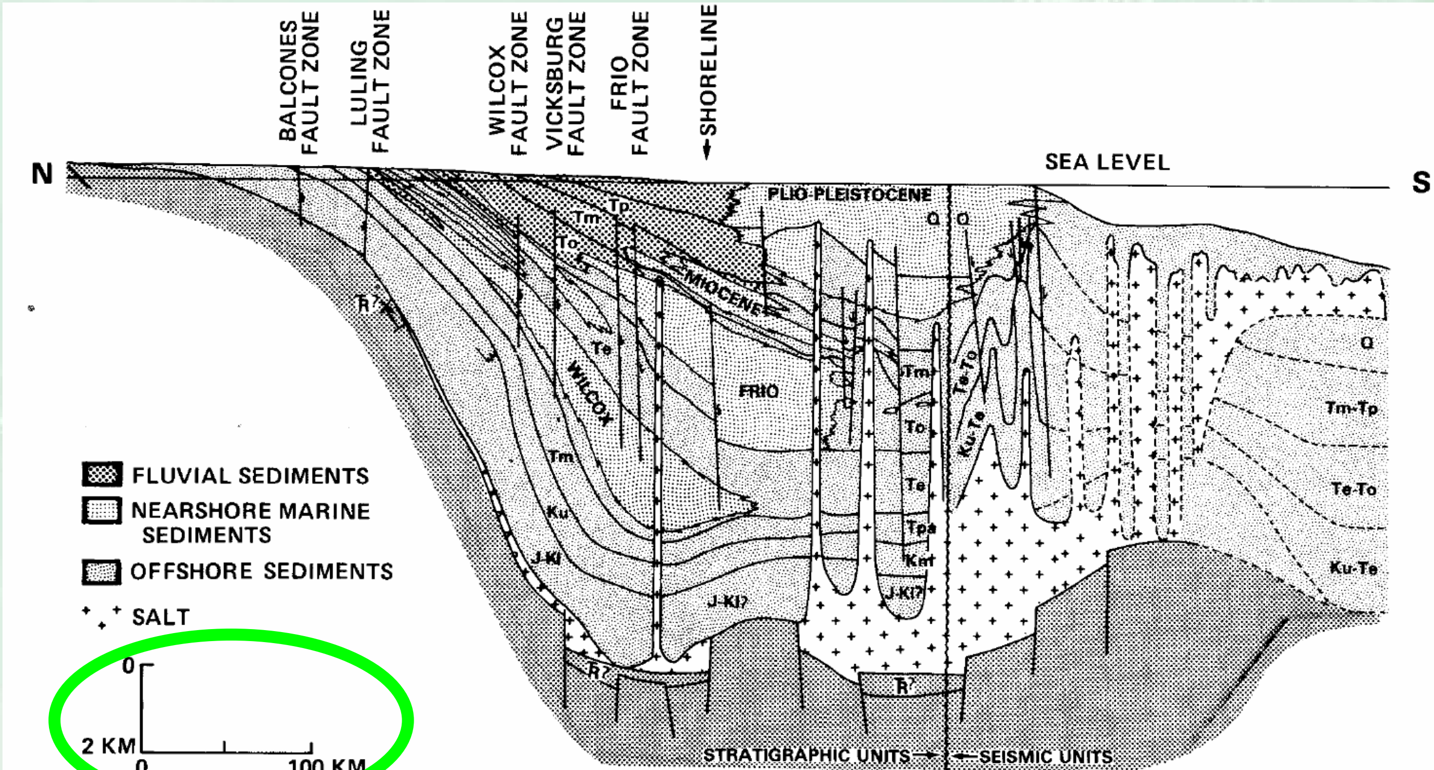
Hydrosphere and Upper Crust:

- Meteoric, including bitterns
- Basinal, including compactional
- Fluids liberated during diagenesis



From Bjørlykke & Høeg, 1993

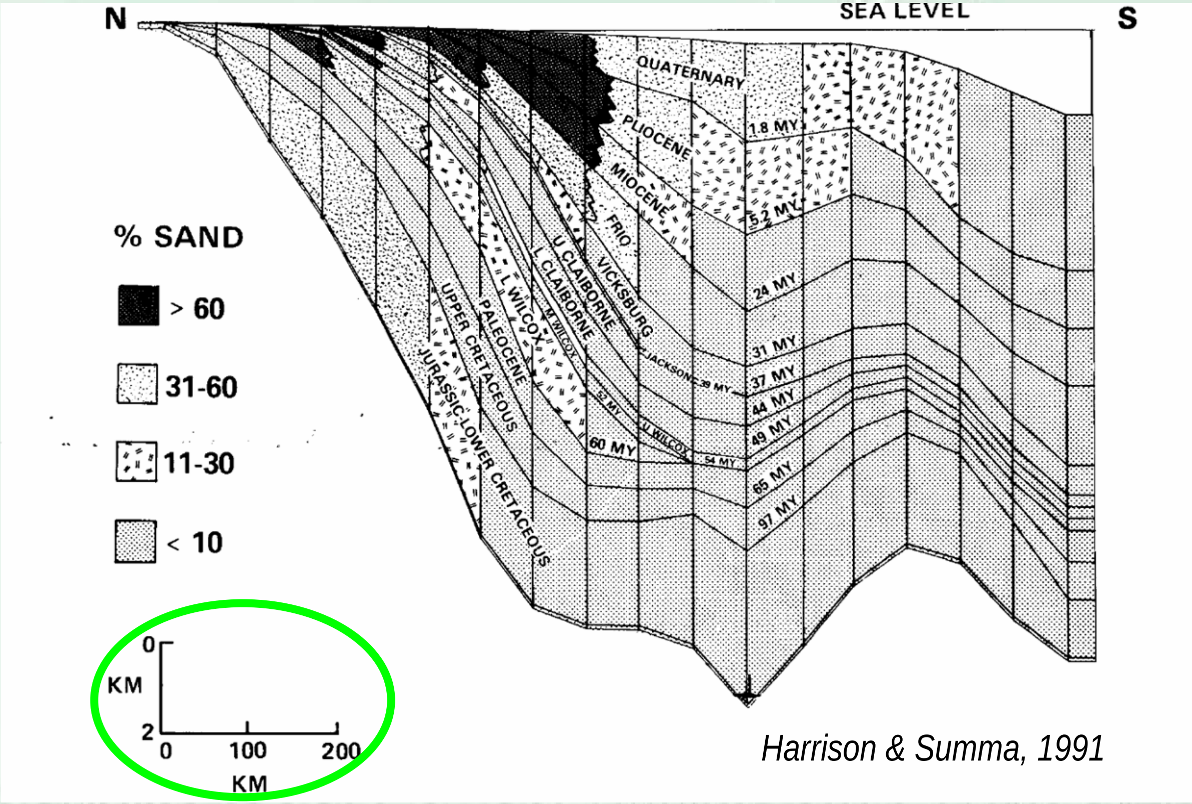
Fluids in Basins: Gulf of Mexico



Harrison & Summa, 1991

- **Mesozoic-Recent sedimentation**
- **Up to 10 km thick – rapid sedimentation**

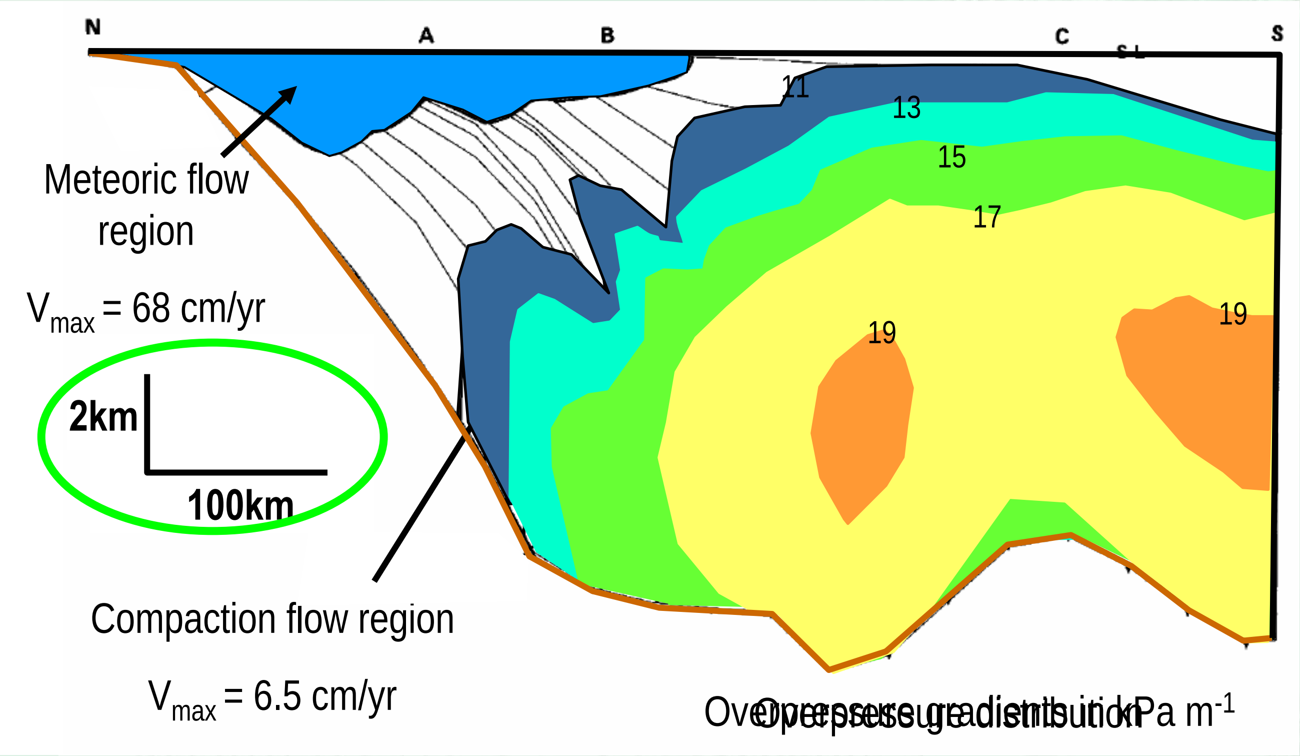
Fluids in Basins: Gulf of Mexico 2



Harrison & Summa, 1991

- **Modelled distribution of lithologies**
- **Based on drilling and seismic data**

Fluids in Basins: Gulf of Mexico 3

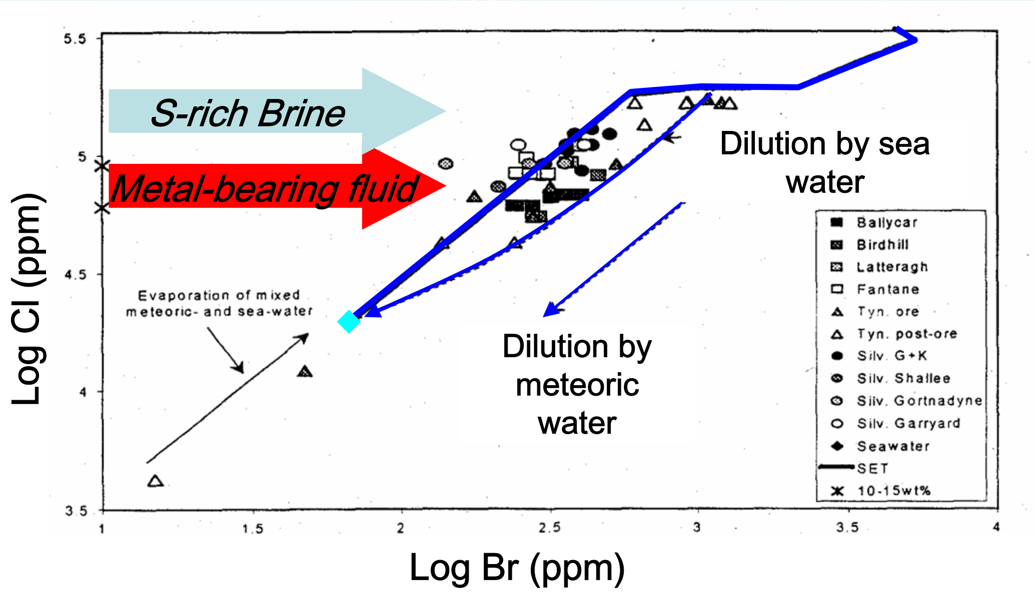


Harrison & Summa, 1991

- **Good match with present day observations**
- **Overpressures dynamic – not related to overt seals**

Tracking Upper Crustal Fluids using Chemistry

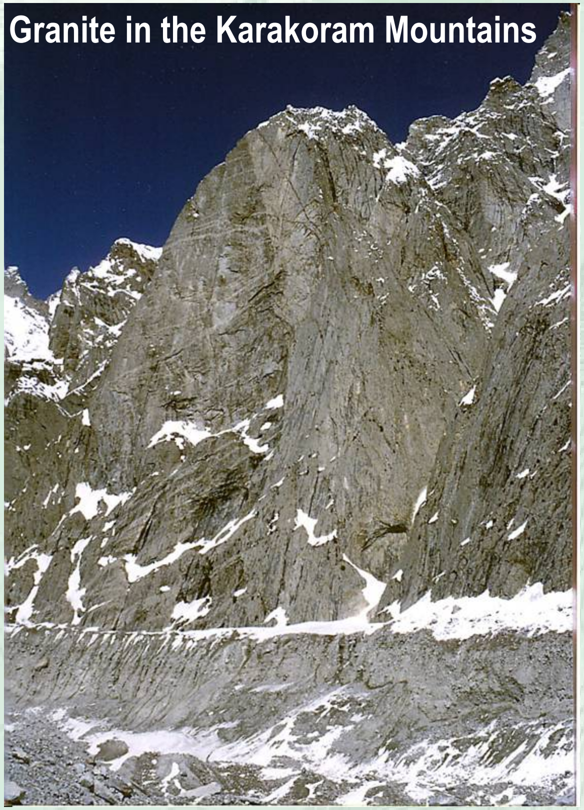
- **Irish deposits and prospects**
- **Two fluids derived from evaporated seawater present; one has reacted with basement**



Gleeson et al., 1999

- **Complex patterns**
  - **Most saline fluids represent sea water evaporated to beyond halite saturation at surface**
  - **Others represent diluted bitterns**

Fluid Sources: 2



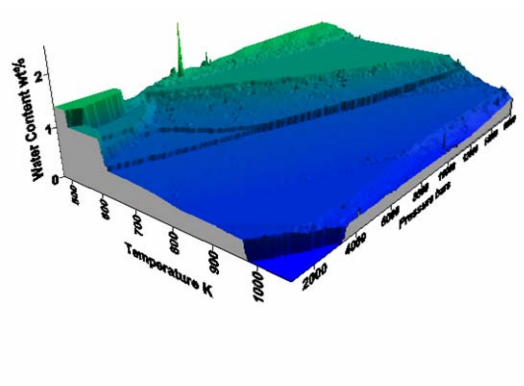
Mid Crustal and deeper:

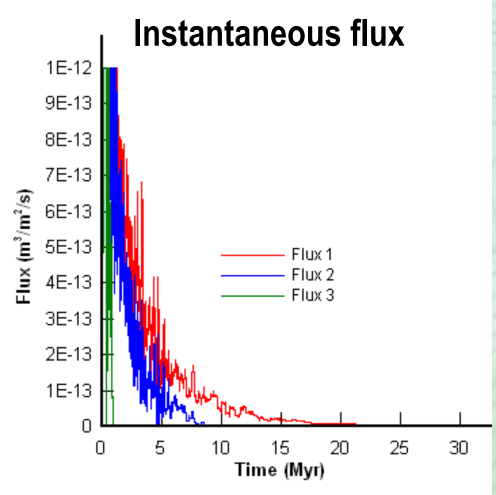
- **Metamorphism**
- **Magmatism**
- **Mantle and other sub-crustal sources**

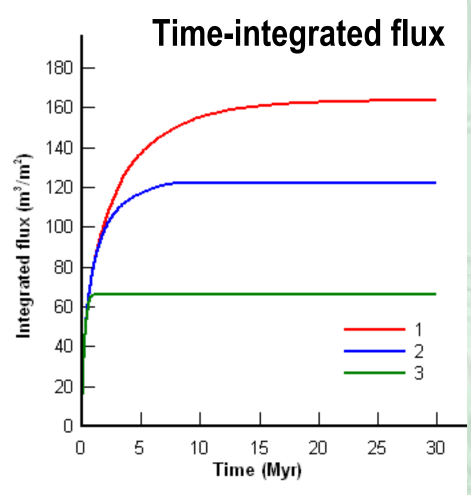
- ***Timing and fluid budgets***

Metamorphic Fluxes

Granite maximum bound water content

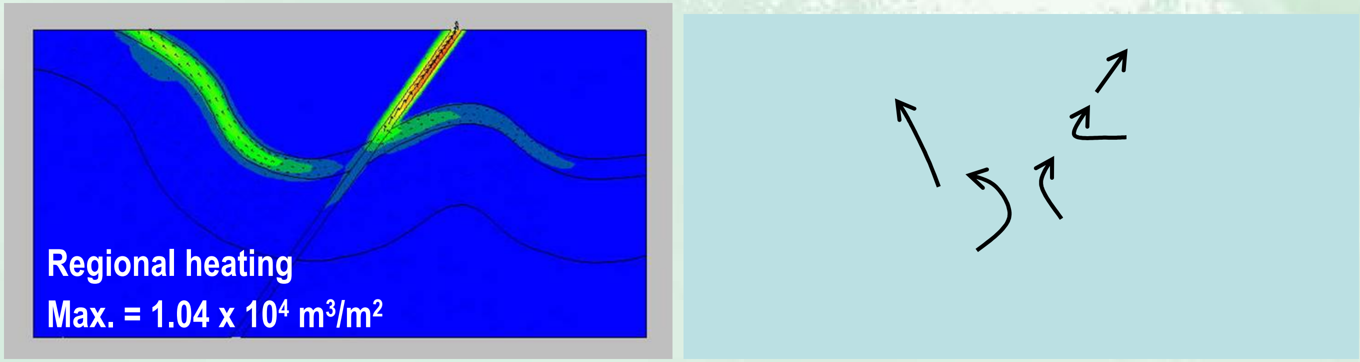






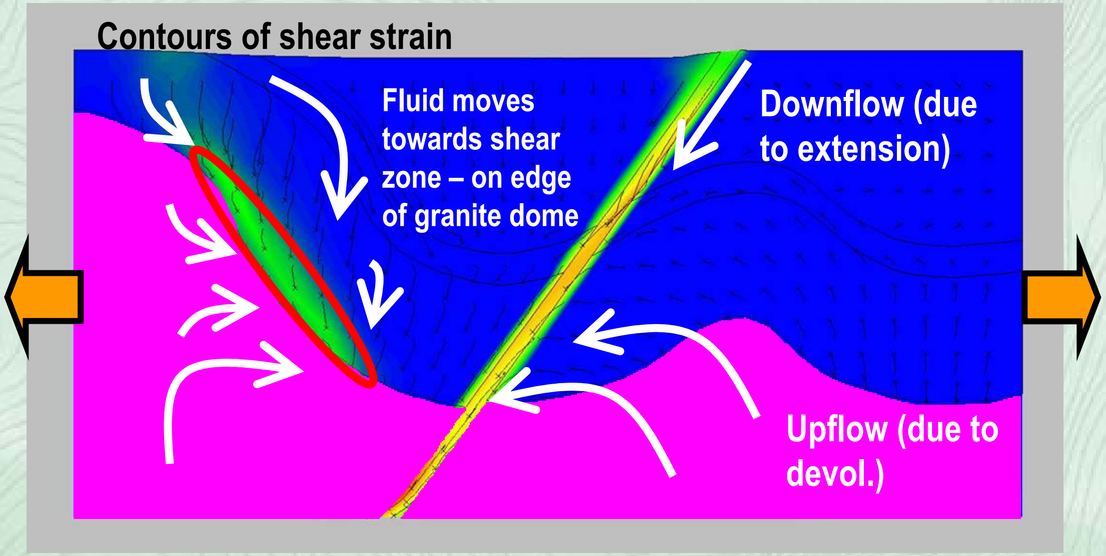
- Heat granitic crust so base at 40km reaches 1200°C
- Monitor flux at different depths in homogeneous crust
- Fluid flux decreases with time as steady state re-established and water lost
  - Modelling by Heather Sheldon

Metamorphic Fluxes



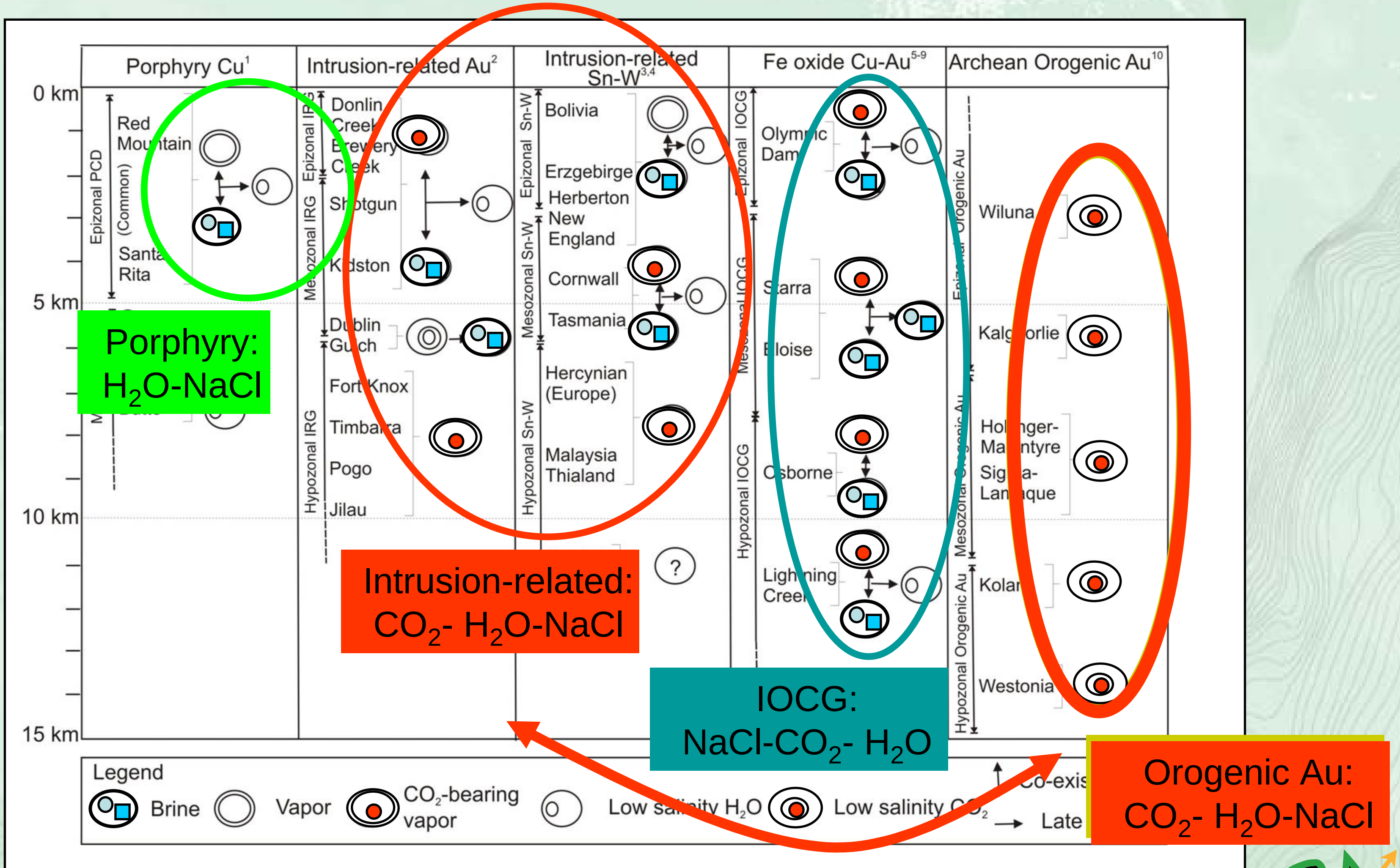
Static devolatilisation

- Upper crustal devolatilisation fluxes focussed – possibly enough
- Extension leads to downflow but facilitates mixing



Devolatilisation during extension

Crustal Fluid Sources



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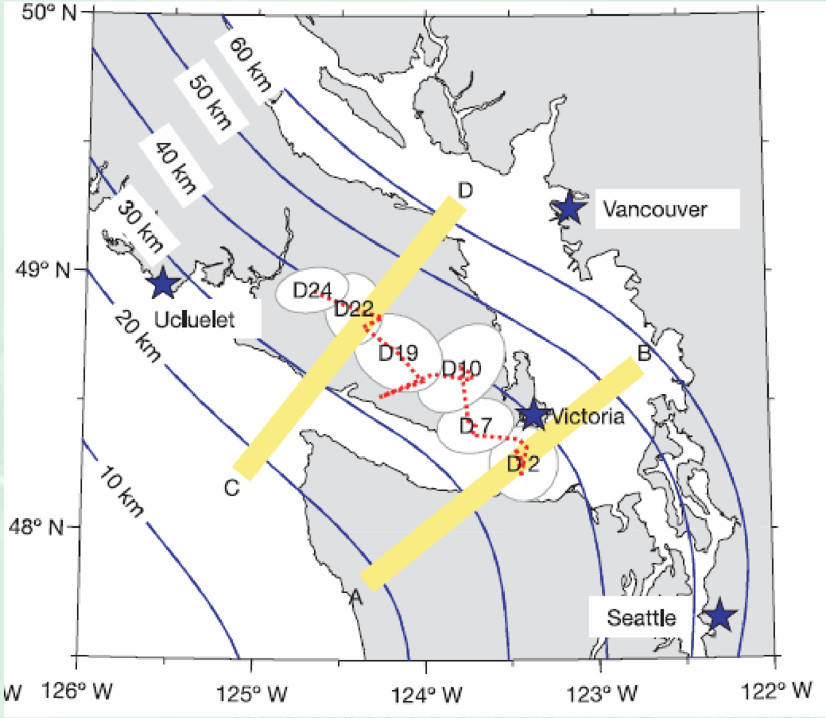
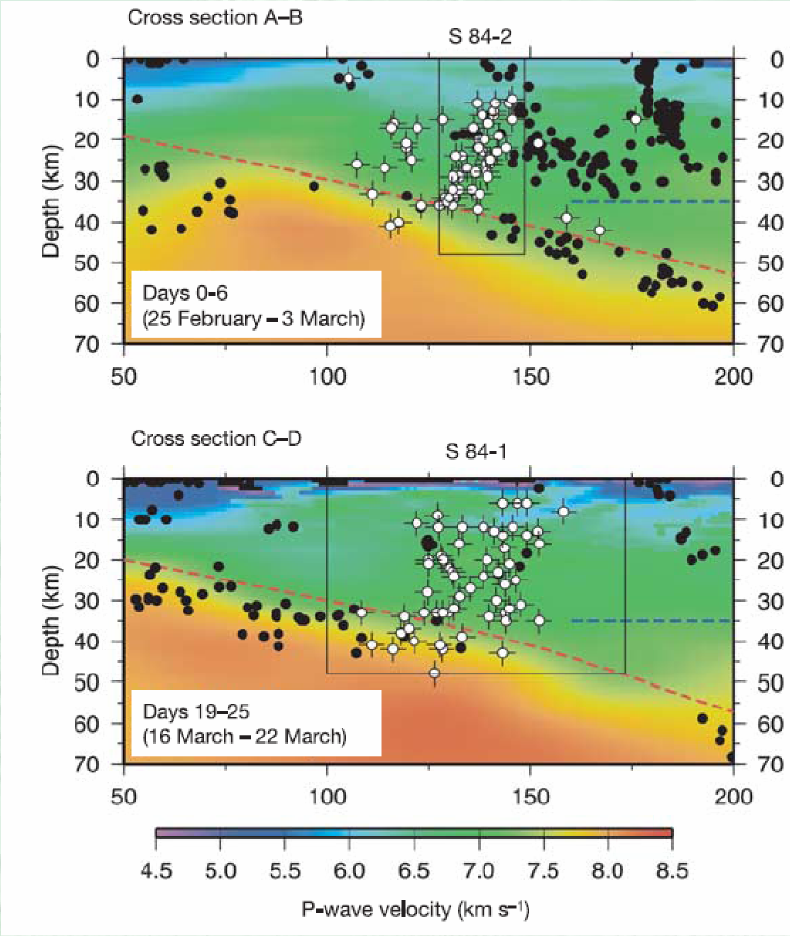
Stolen from a Tim Baker paper

Sub-Crustal Fluid Reservoirs





Kao et al, 2005

- **Cascadia Margin**
- **Tremor swarms indicative of fluid movement**
- **Fluid sourced from dewatering slab?**

Fluid Sources: 3

- **Fluids are only available at certain times and places in the geological evolution of an area**
- **‘Surface’ fluids (basinal; diagenetic) transient unless a pathway is created to sealed compartments or the surface**
- **Fluxes?**

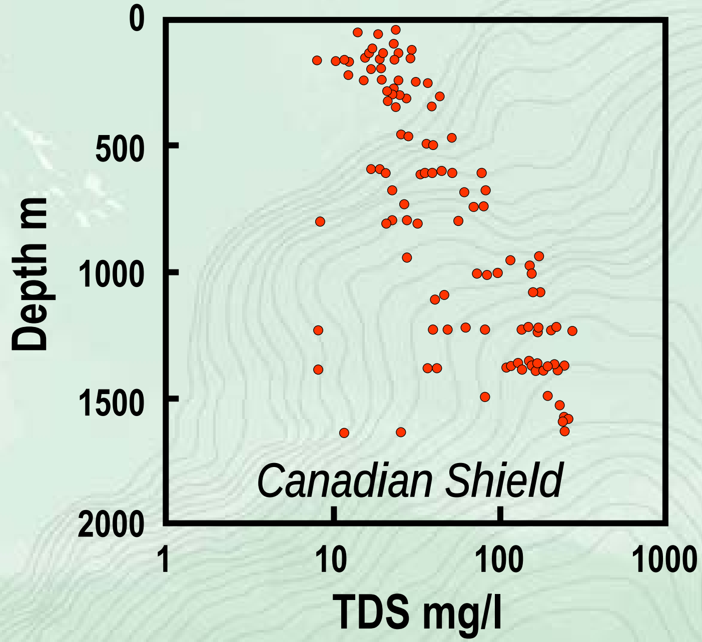
A. Creating Hydraulic Potential Gradients

- Topographic relief
- Fluid pressure changes induced by deformation
  - Compaction is a subset of this
- Convection induced by thermal or chemical buoyancy
- Fluid pressure changes generated by chemical reactions
  - Diagenesis, hydrocarbon generation, metamorphism
- Pressure gradients generated by fluids released from magmas

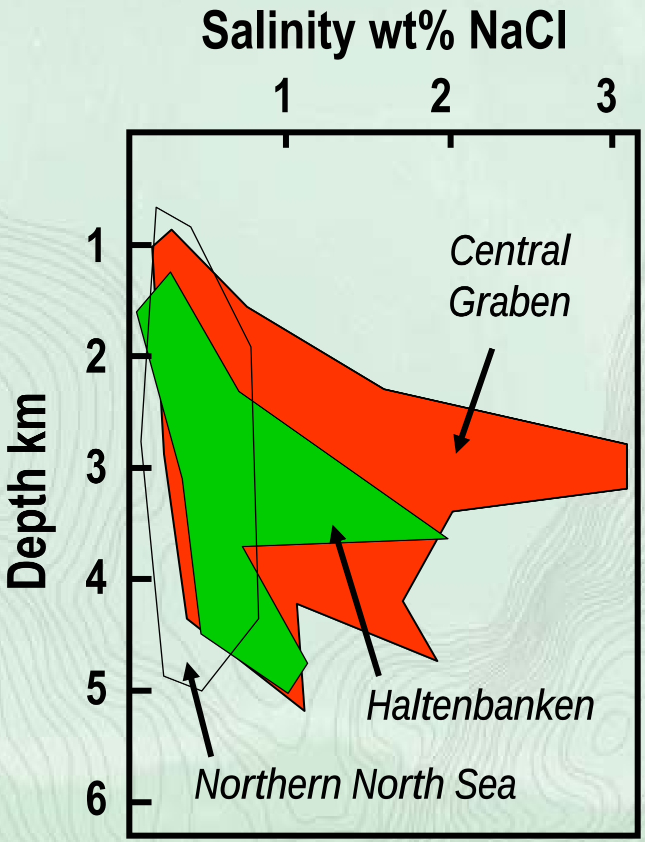
After Bruce Hobbs

Upper Crustal Fluid Migration

- **Salinity distributions imply a lack of convection**
  - **And real difficulty in establishing it**



Deming, 1994



Bjorlykke & Gran, 1994

B, C. Pathways

Permeability maximised *over time* where:

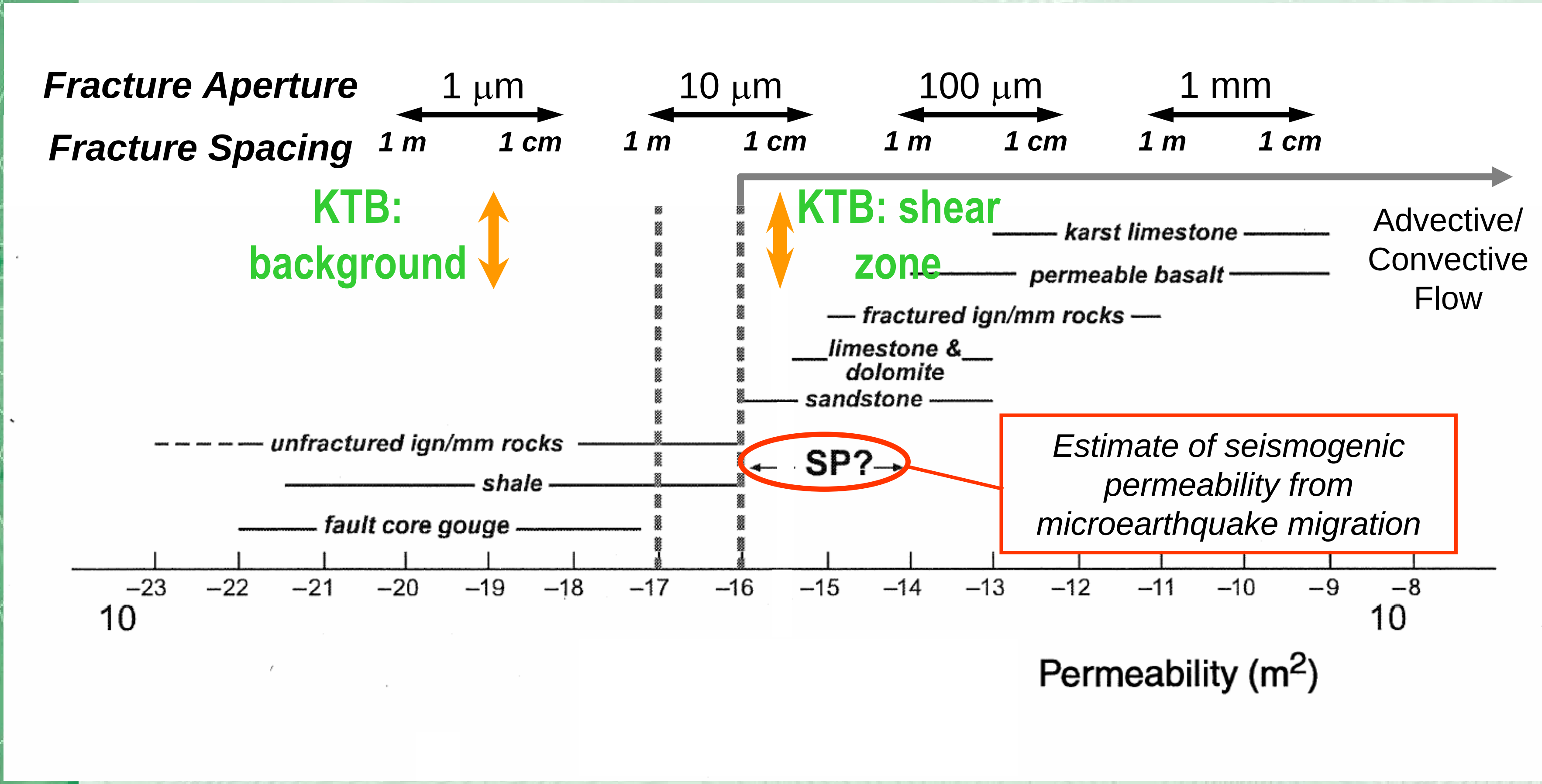
- **deep structures can be repeatedly reactivated**
- **structures intersect**
- **damage zones develop**
- **mineral dissolution occurs**

C. Permeability Generation and Destruction

- **Competition between**

1. **Permeability Creation**
   - **Deformation**
     - Extensional and compressional
   - **Increase in porosity due to reaction**
2. **Permeability Destruction**
   - **Compaction (not just in basins)**
   - **Decrease in porosity due to mineral precipitation**

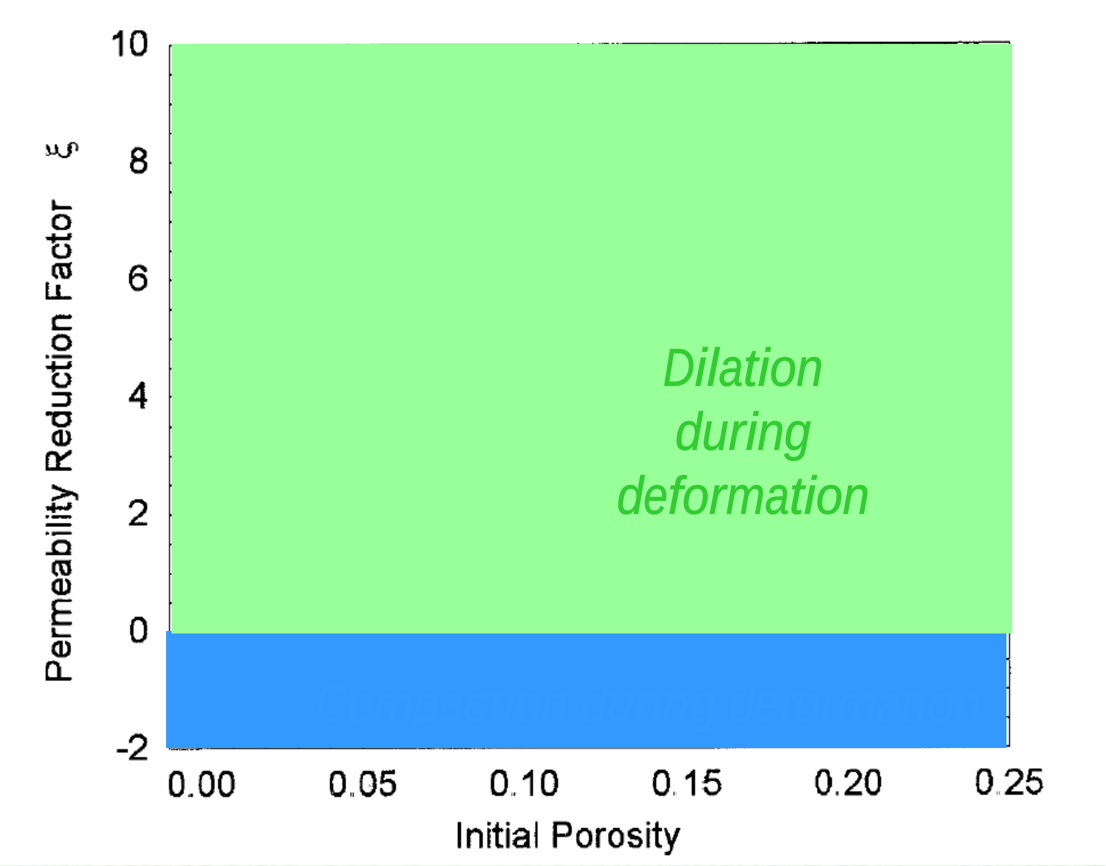
Permeability Values



Based on Rowland & Sibson, 2004

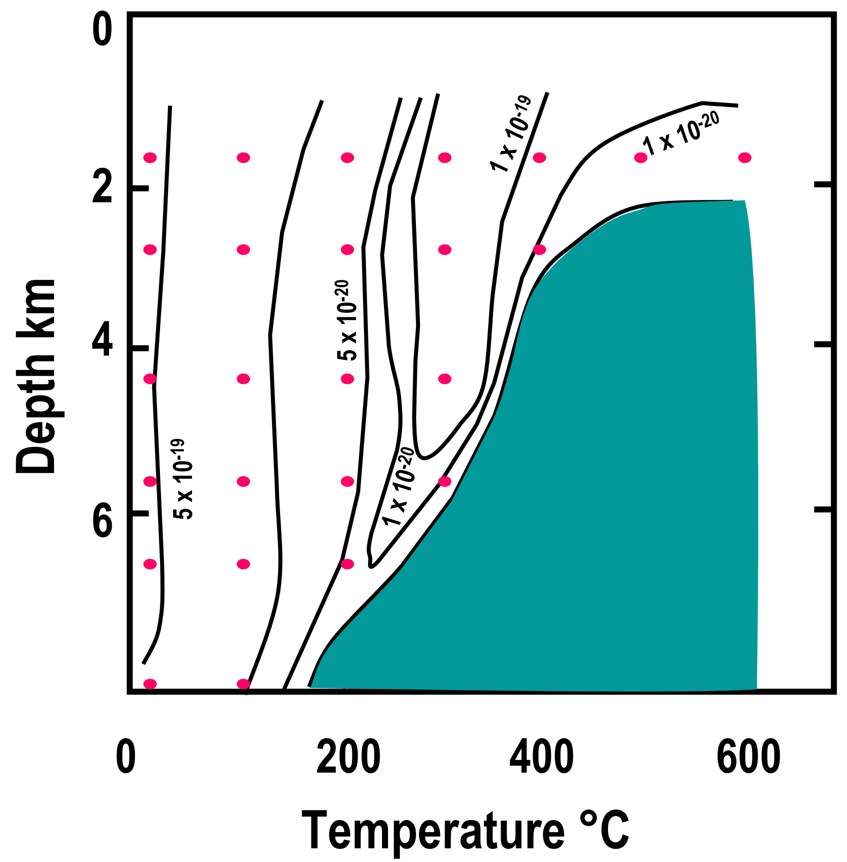
Data from McDermott et al., 2006

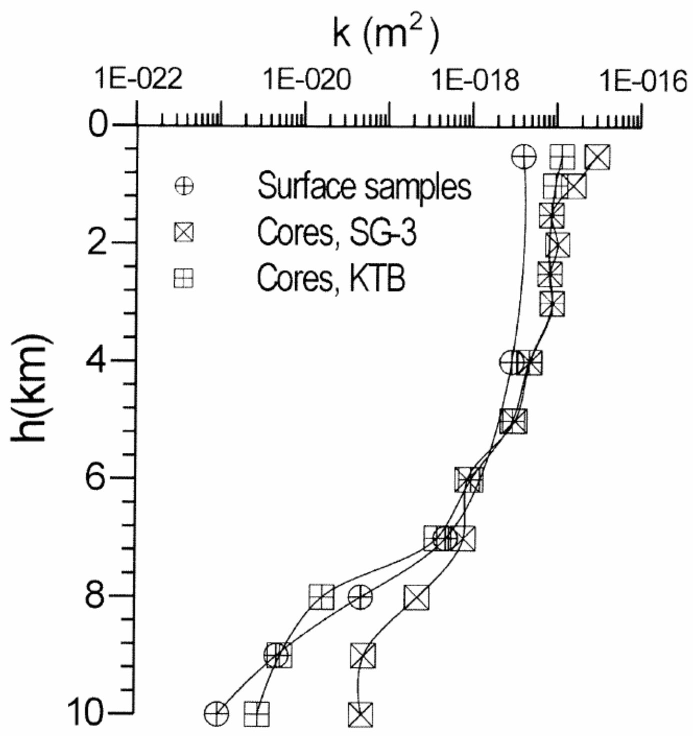
Fault Permeability and Rock Type



- **Ductile regime – variation in permeability with lithology**
- **Brittle regime – variation in permeability with porosity**
- **When do fault permeabilities depend on host lithologies?**

Permeability Variation

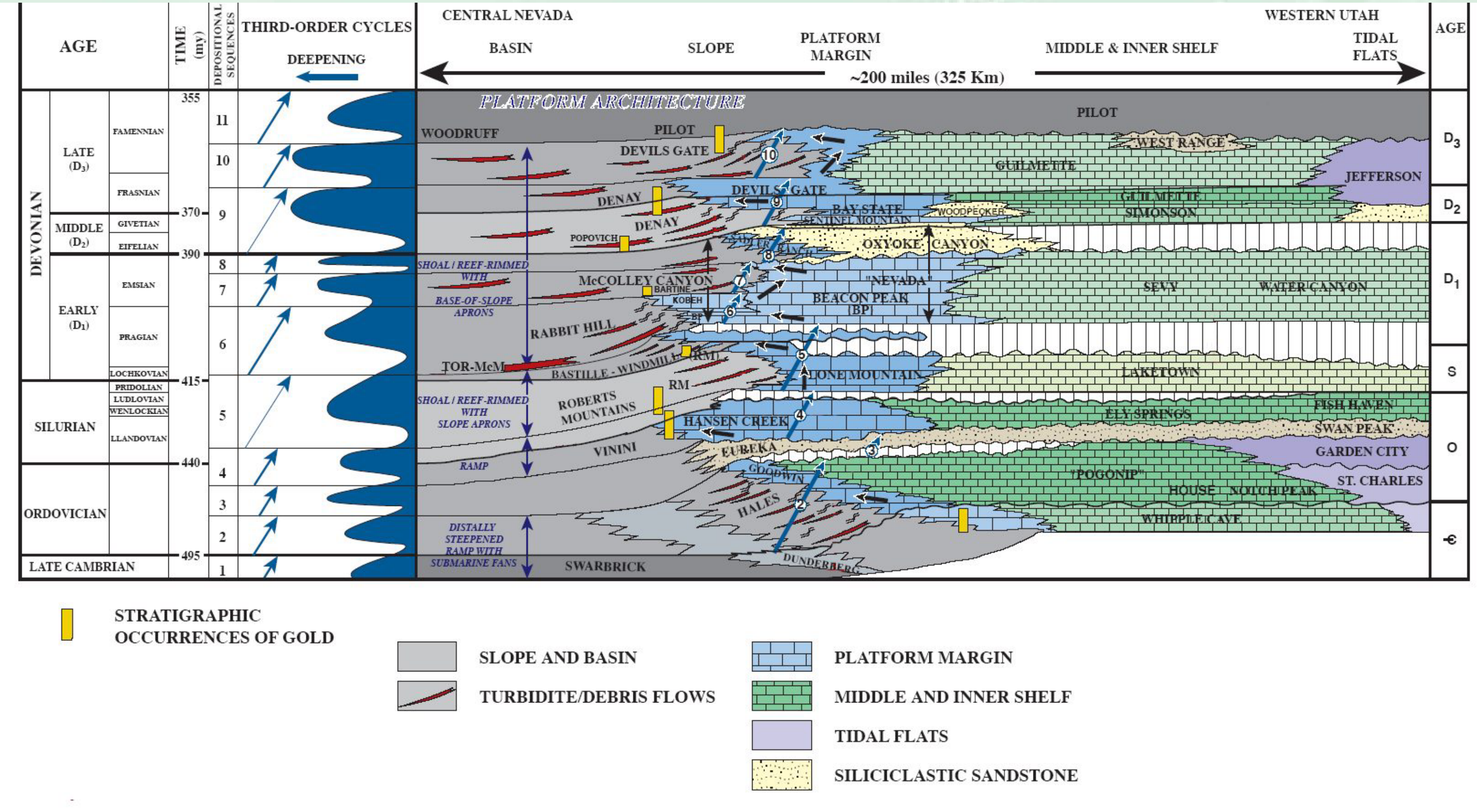




Zharikov et al., 2005

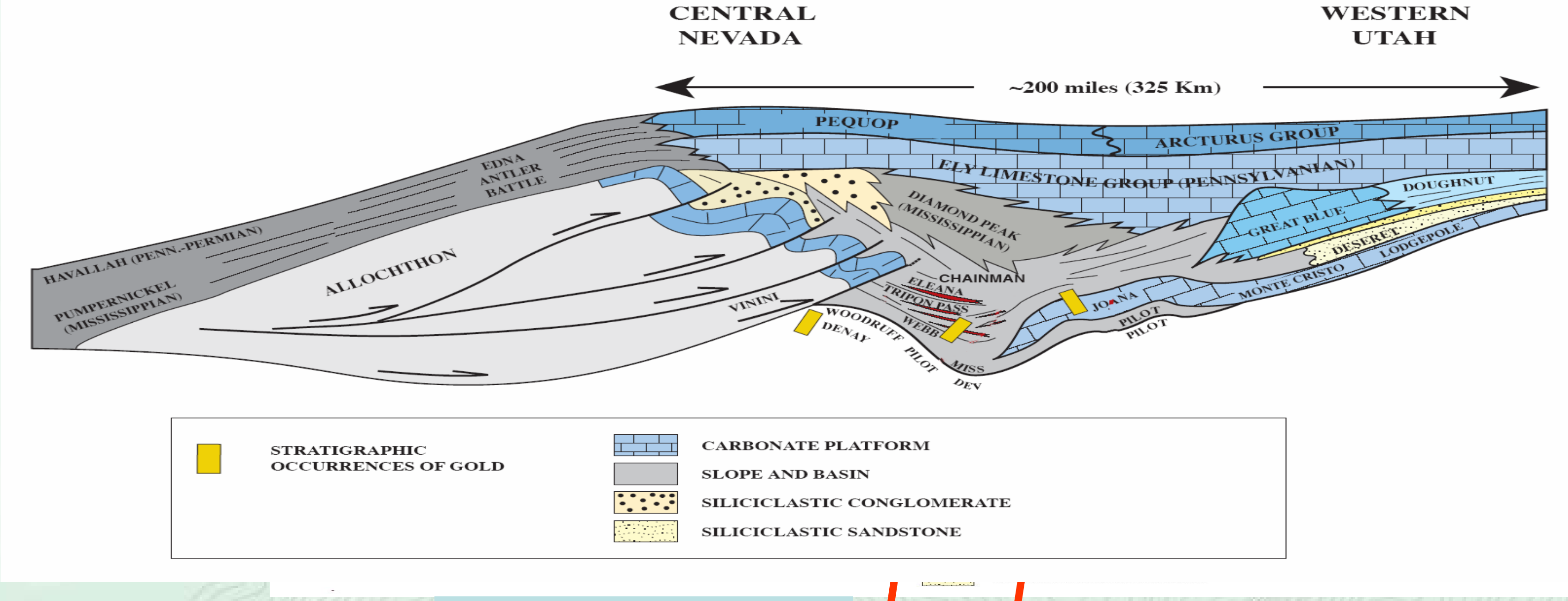
- **Permeability of plugs from Kola borehole**

Great Basin USA: Lower Palaeozoic Architecture



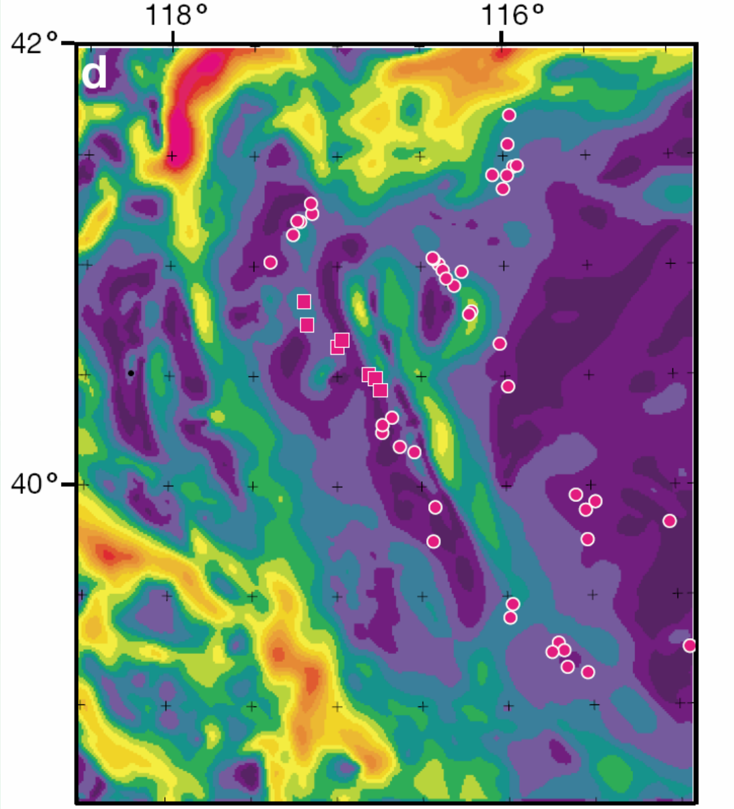
Cook & Corboy, 2004

Great Basin: Controls on Architecture

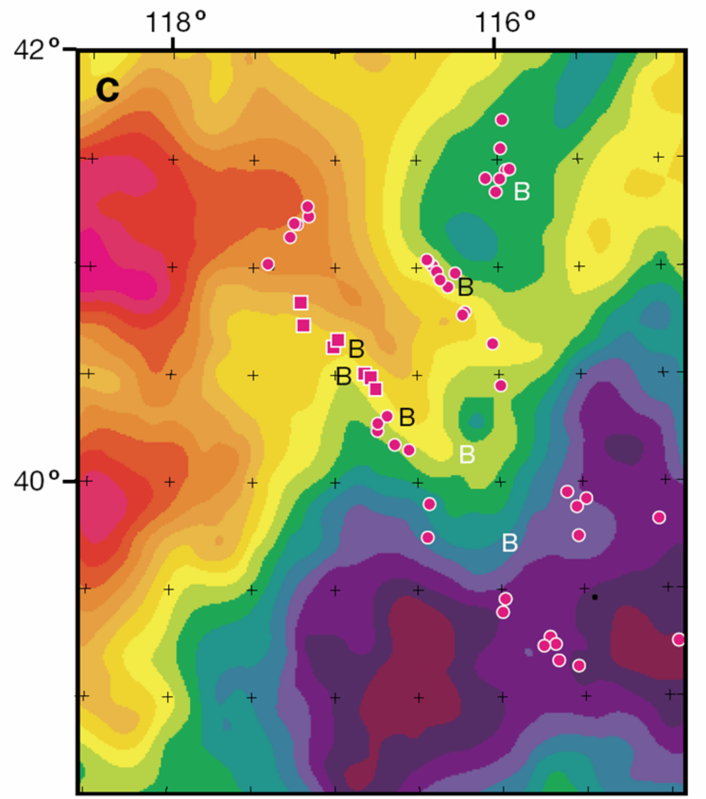


Deep Structures seen in Geophysics as well as isotope data etc.

Great Basin: Architecture



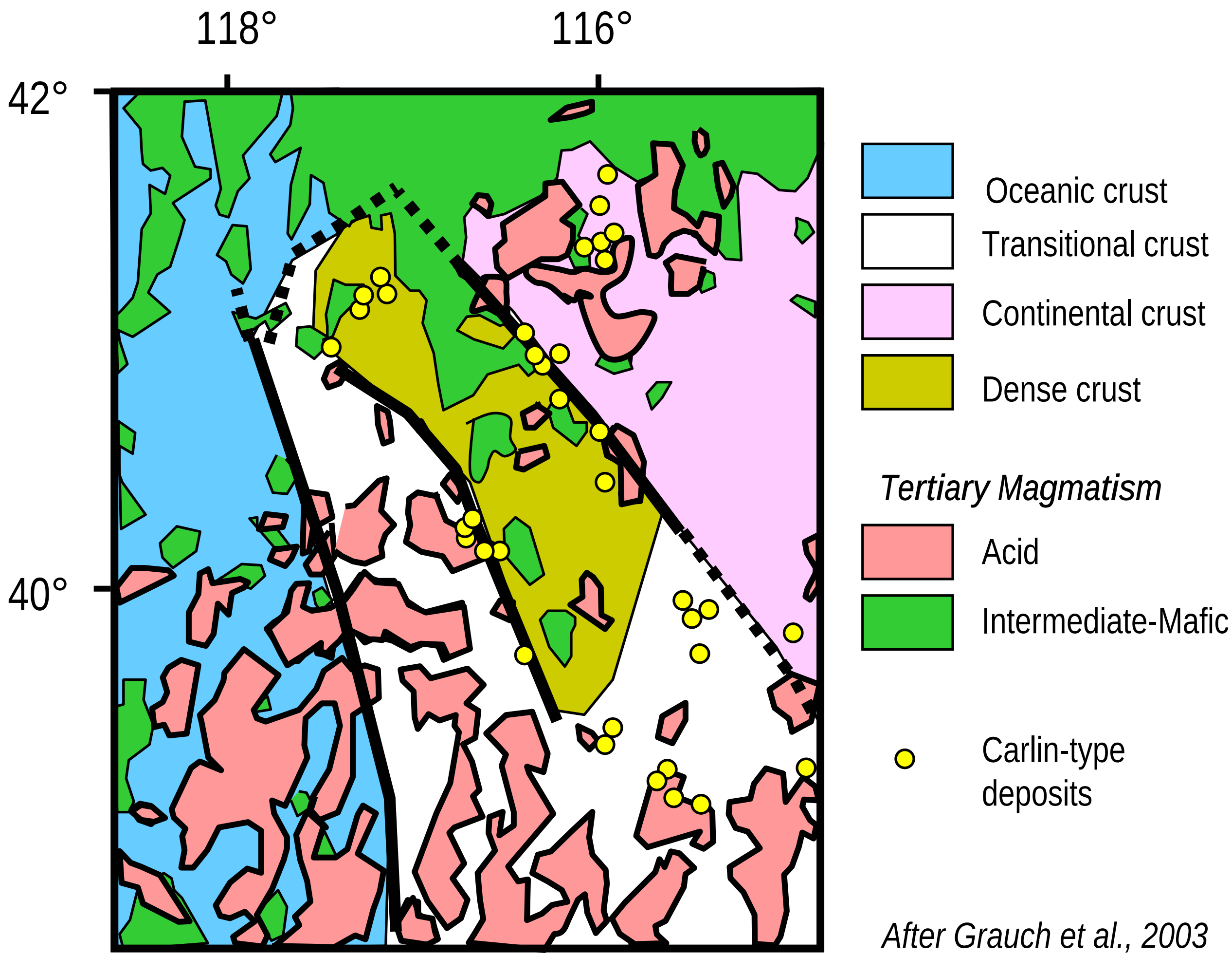
Horizontal-gradient magnitude (HGM)



Bouguer gravity minus basin effects, up 5 km

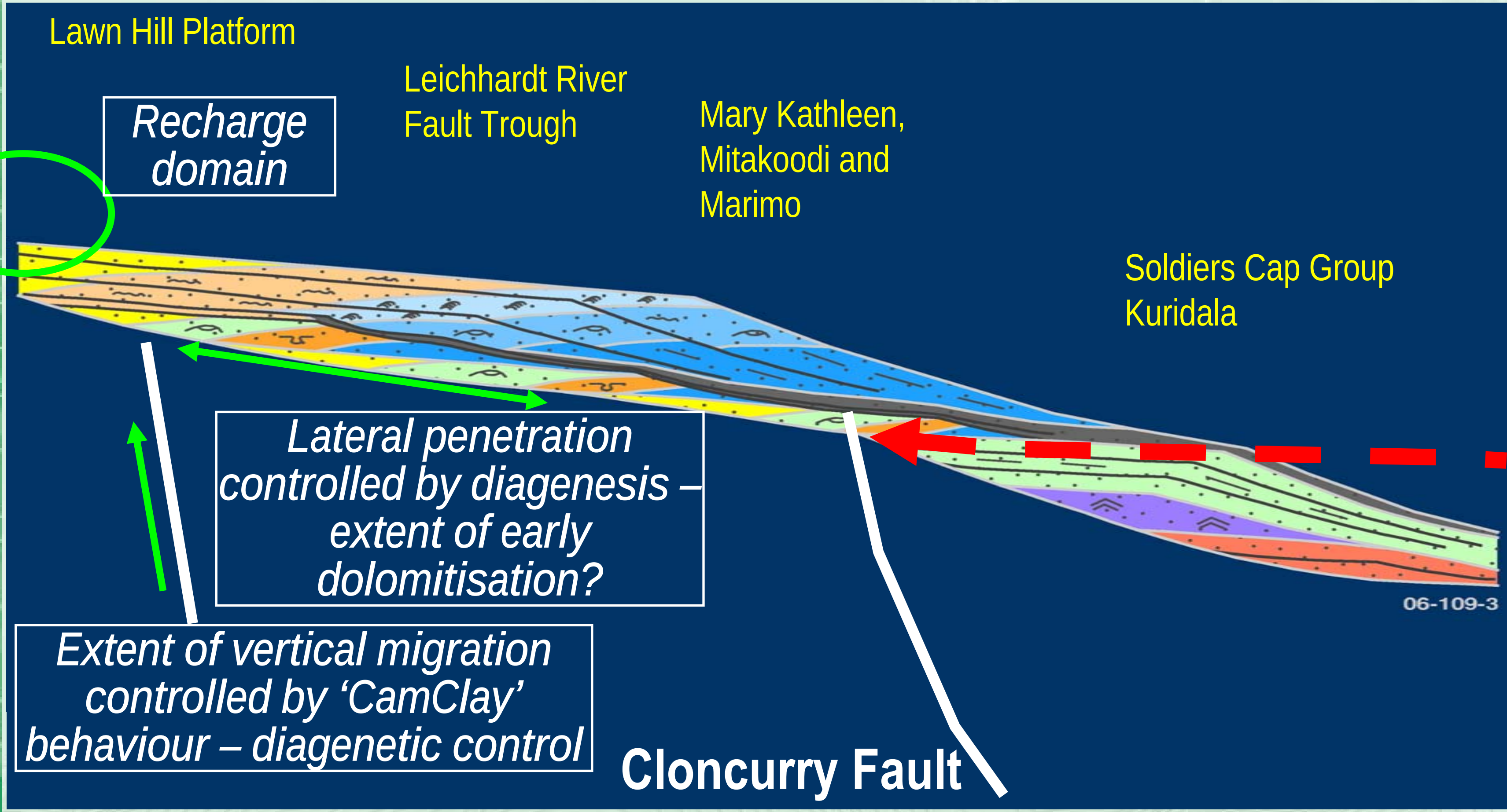
From Grauch et al., 2003

Great Basin: Geodynamics



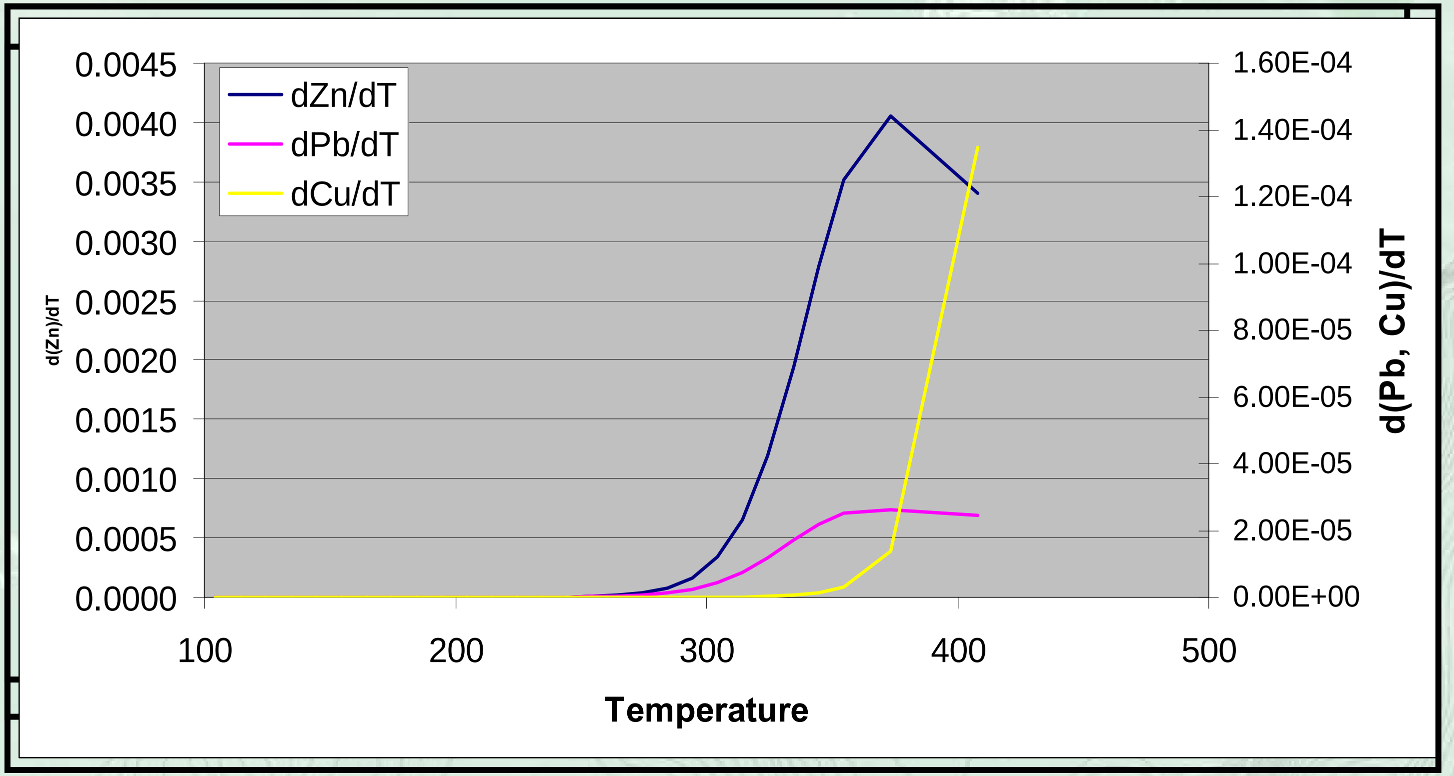
After Grauch et al., 2003

Mt Isa Sediment Architecture 1690 – 1650 Ma



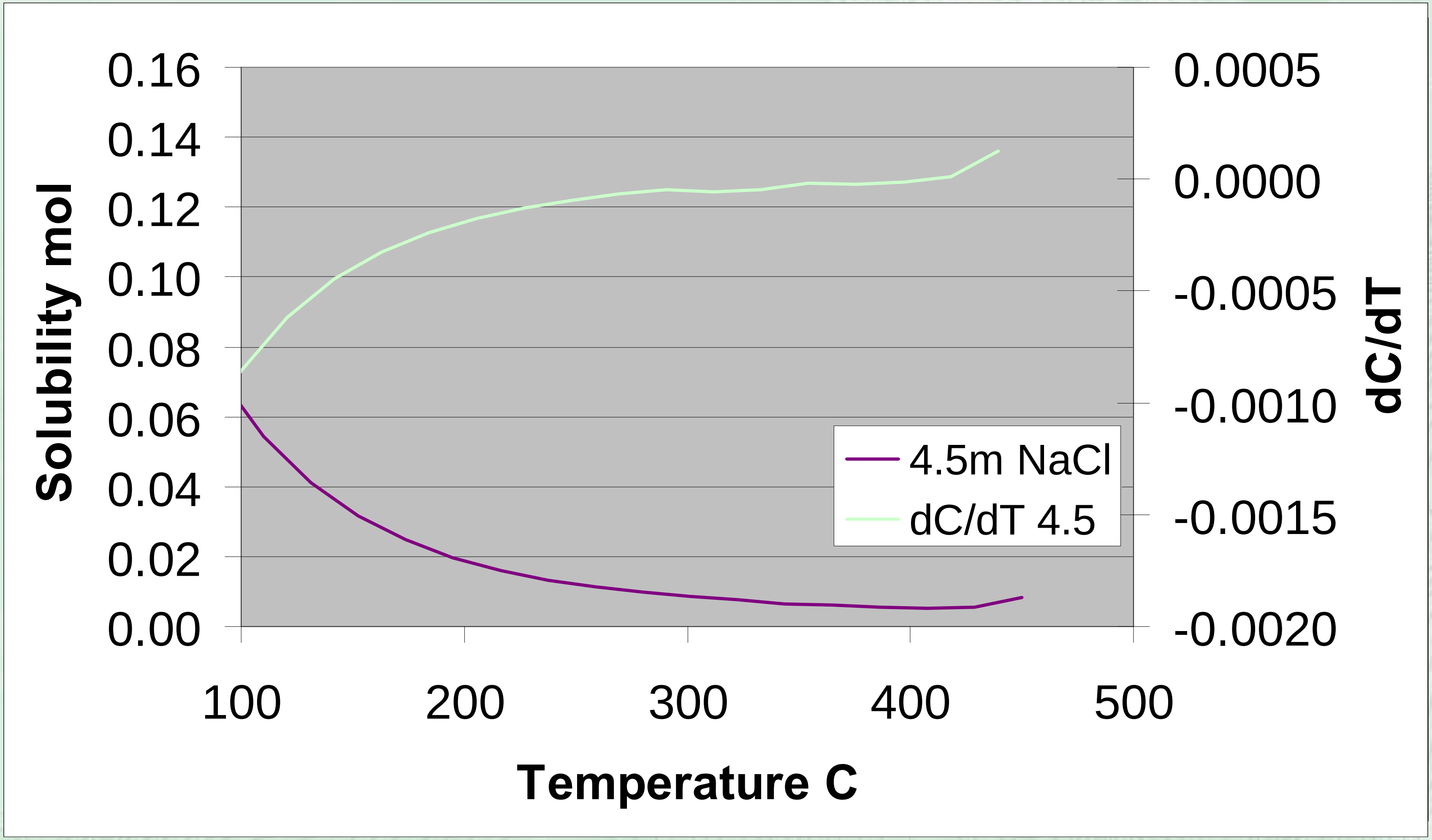
From Peter Southgate

D. Solubility Sensitivity - Temperature



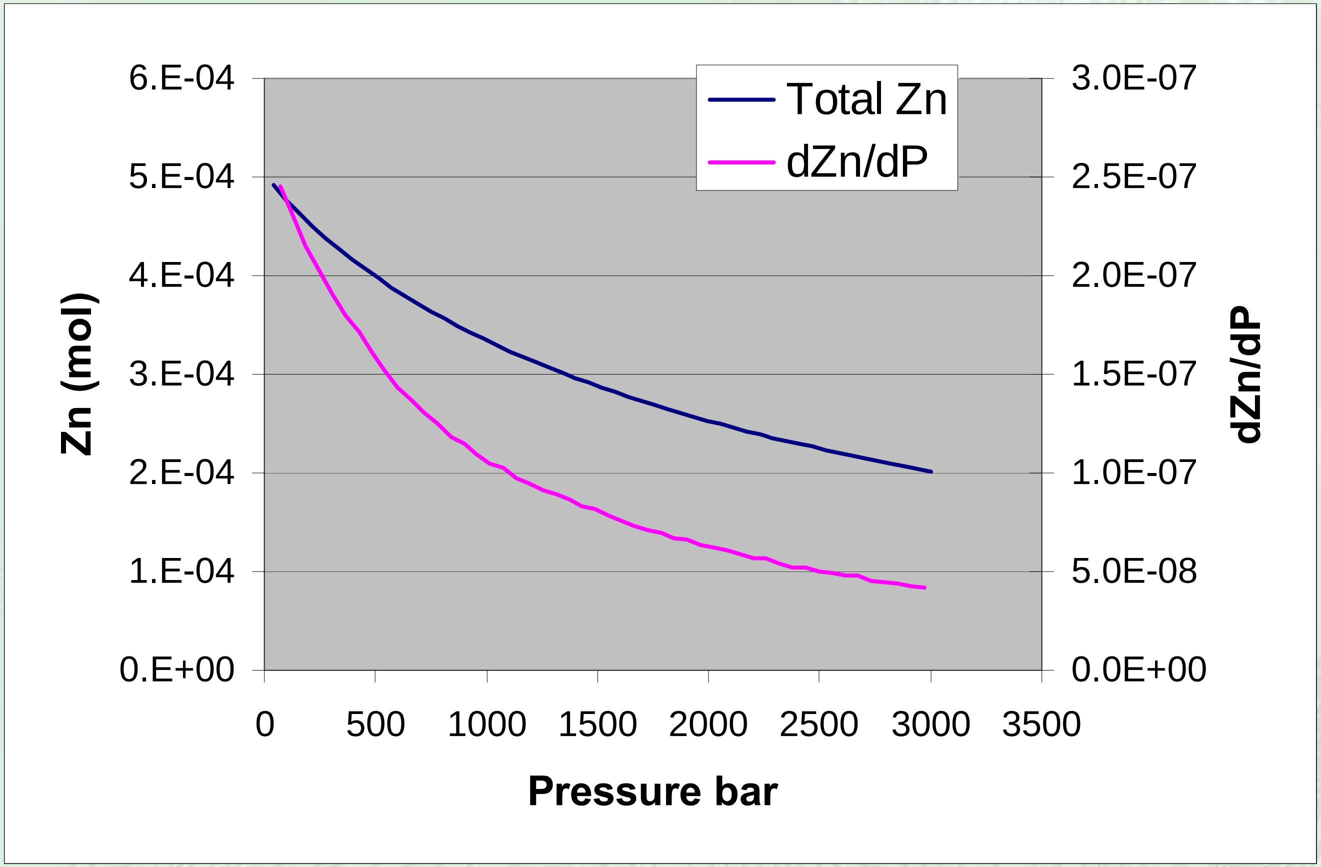
- **Solubility of Zn (sphalerite), Pb (galena) and Cu (chalcopyrite) at 1 kbar**
  - **pH controlled by K-feldspar-muscovite-quartz**
  - **ΣS = 0.01m**
  - **Redox controlled by haematite-magnetite**

Solubility Sensitivity - Temperature



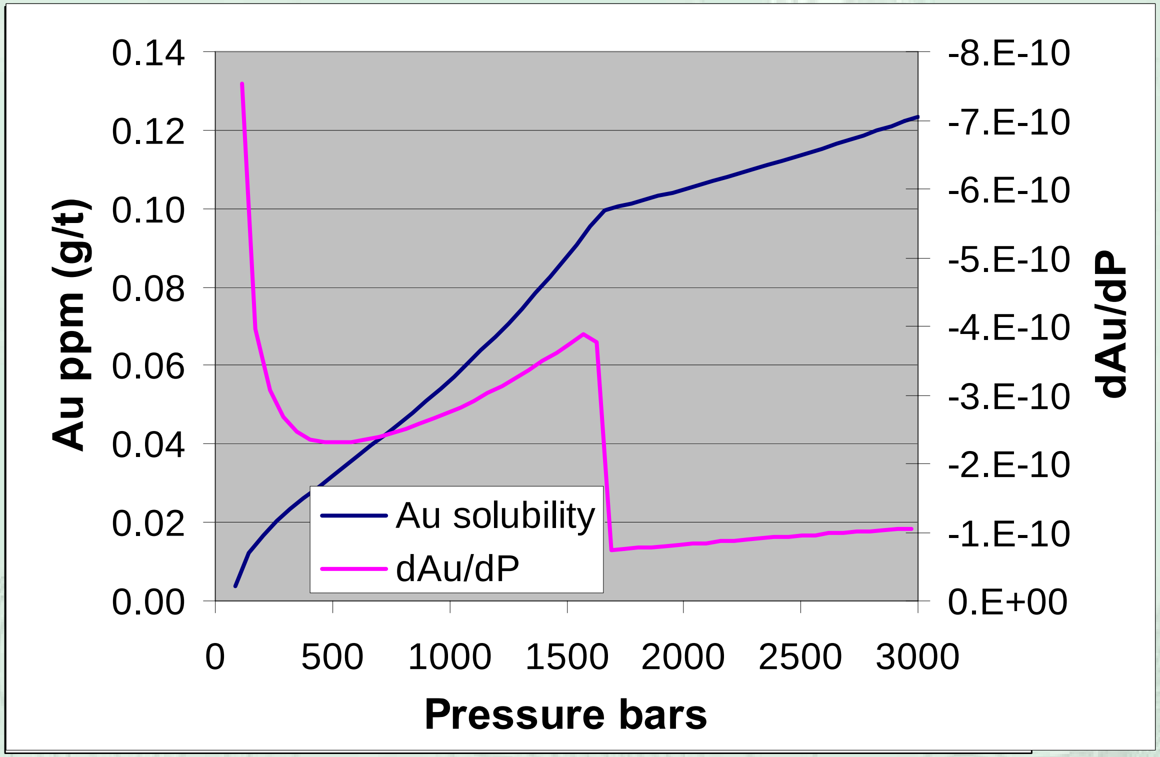
- **Ca in solution controlled by Anhydrite at 500 bars**

Solubility Sensitivity - Pressure



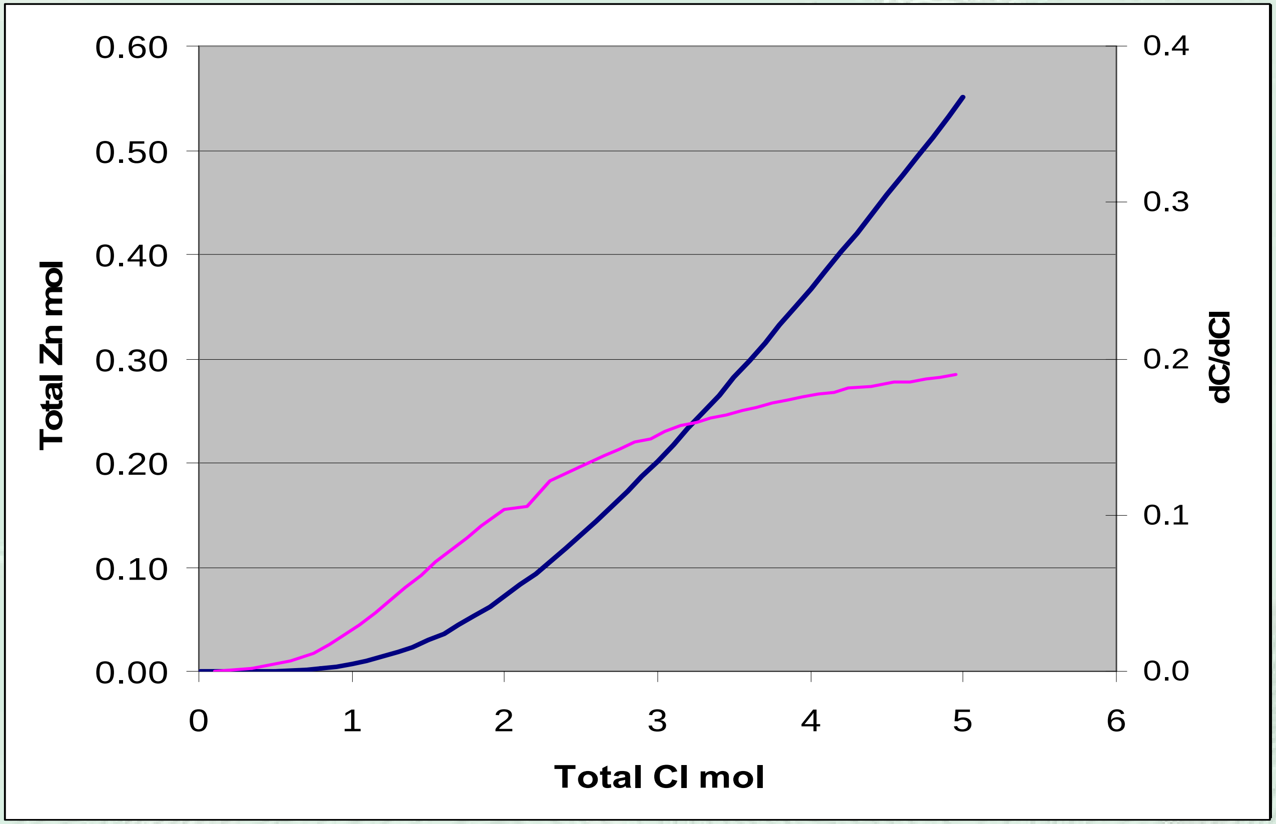
- **Solubility of Zn (sphalerite) at 250°C**
  - **pH controlled by K-feldspar-muscovite-quartz**
  - **$\Sigma S = 0.01m$**
  - **Redox controlled by haematite-magnetite**

Solubility Sensitivity - Pressure



- **Solubility of Gold at 300°C**
  - **pH controlled by K-feldspar-muscovite-quartz**
  - **SS = 0.01**
  - **Redox below Haematite-magnetite**
  - **Gas allowed to escape once formed**

Solubility Sensitivity - Chemistry

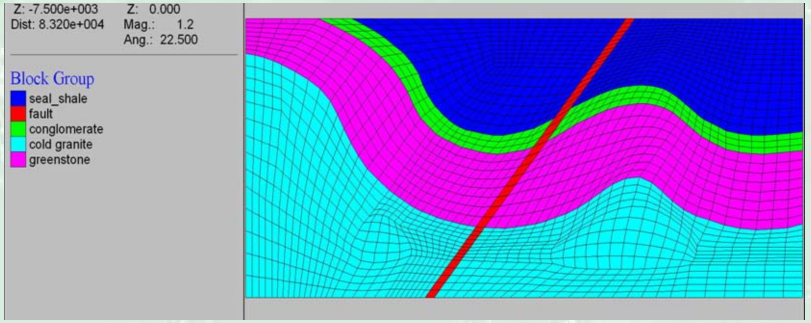


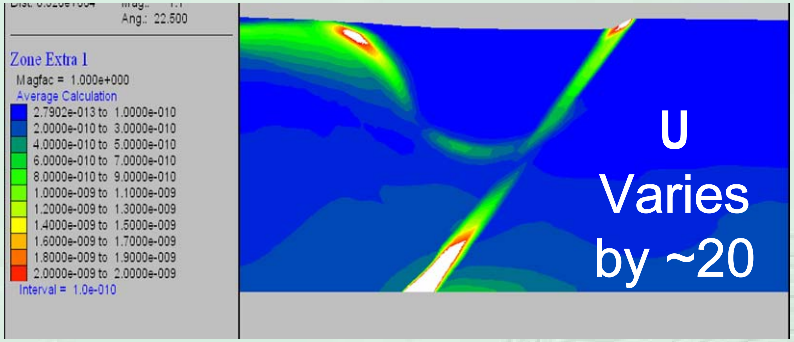
- **Solubility of Zn (Sphalerite) at 1kbar**
  - pH controlled by K-feldspar-muscovite-quartz
  - $\Sigma S = 0.01m$
  - Redox controlled by haematite-magnetite

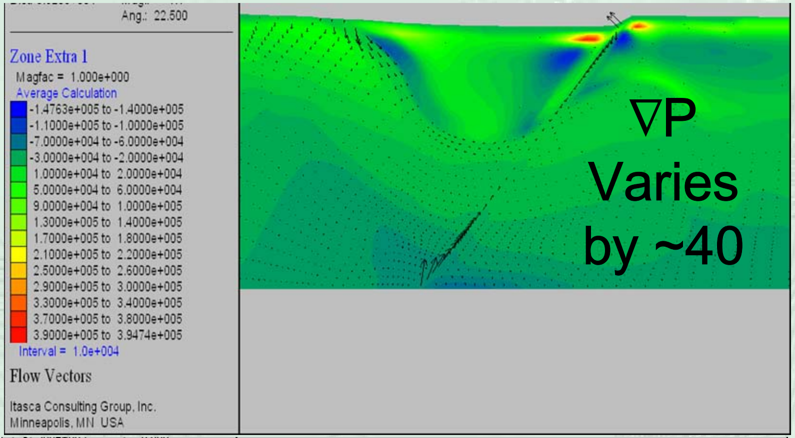
P, T, C Gradients and Deposition

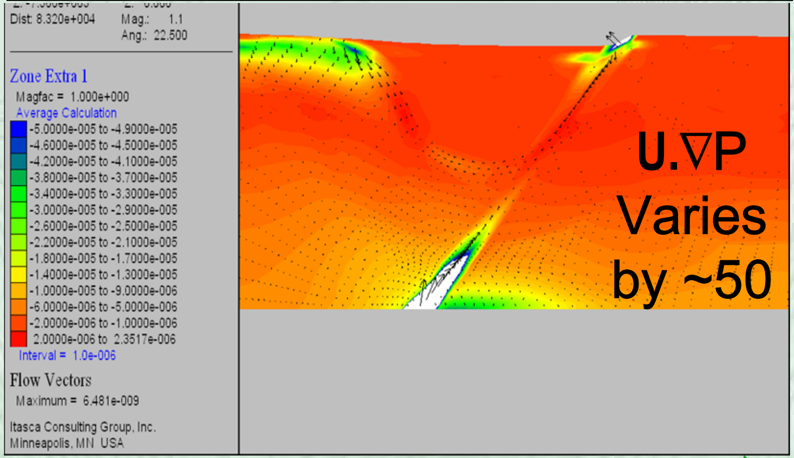
- **Temperature gradients**
  - **Steepest near surface or around igneous centres**
- **Pressure gradients**
  - **Greatest (transiently) in dilation sites**
- **Can induce unmixing**
- **Chemical gradients**
  - **Fluid-rock disequilibrium**
    - Due to both temperature and compositional effects
  - **Fluid mixing**
    - Efficacy demonstrated e.g. in Ireland

E. Spatial Gradients in T, P & C





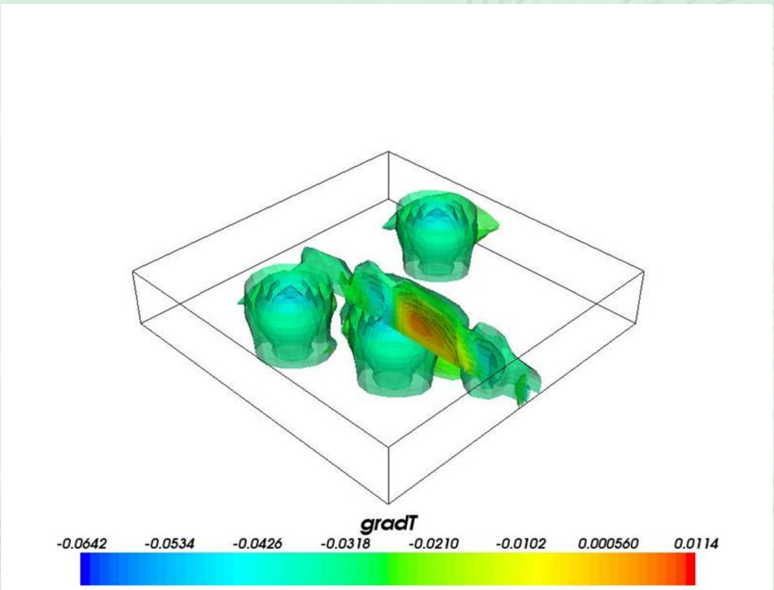




- **Yilgarn late basin models of Yanhua Zhang**
  - **Plots generated specially by Heather Sheldon**

Spatial Gradients in T, P & C

- **Yilgarn granite convection models run by Julia Blockeel**
  - **Plots generated specially by Heather Sheldon**

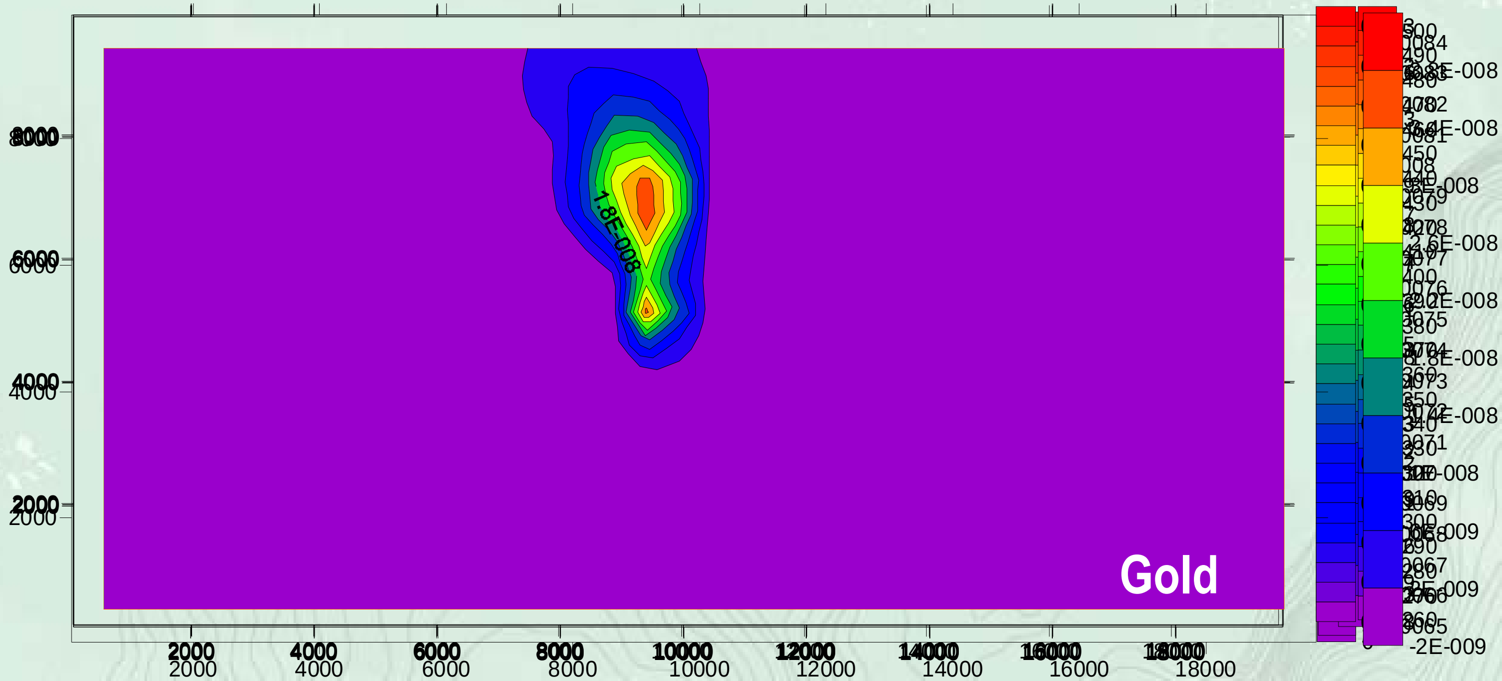


- **Velocity varies by a factor of ~10^6**
- **∇P and ∇T change by ~10**

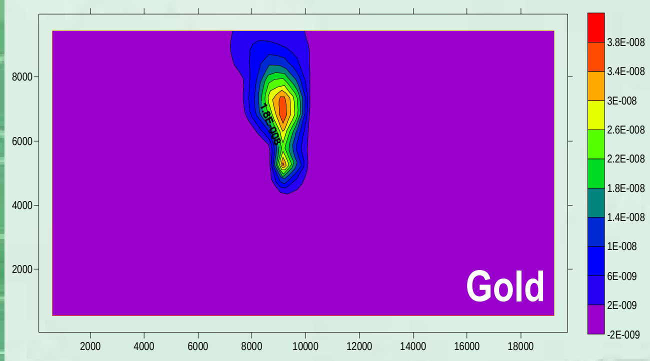
	Spatial Gradient	Solubility Sensitivity	Spatial Sensitivity mol m^{-1}
P (Zn)	~10^3 Pa m^{-1}	10^{-9} mol Pa^{-1}	10^{-6}
P (Au)	~10^3 Pa m^{-1}	10^{-15} mol Pa^{-1}	10^{-12}
T (Zn)	~10^{-2} K m^{-1}	2 x 10^{-3} mol K^{-1}	2 x 10^{-5}
T(Au)	~10^{-2} K m^{-1}	3 x 10^{-9} mol K^{-1}	3 x 10^{-11}

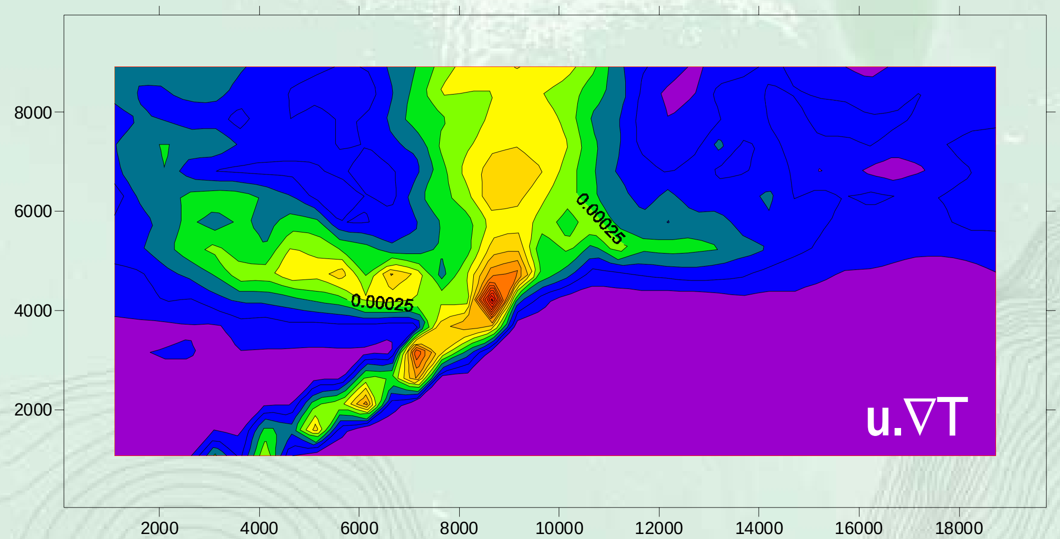
Spatial Gradients in T, P & C

- **Reactive transport model of James Cleverley**

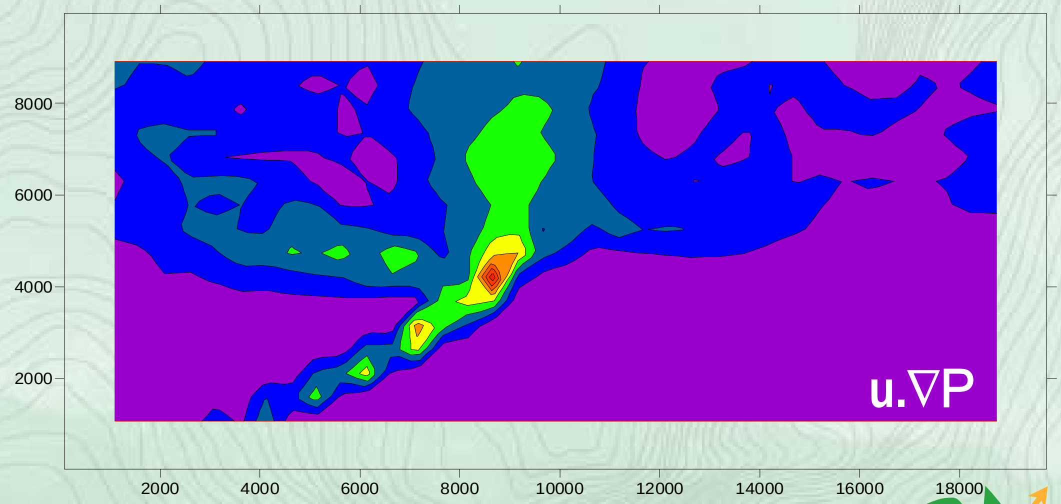


Spatial Gradients in T, P & C

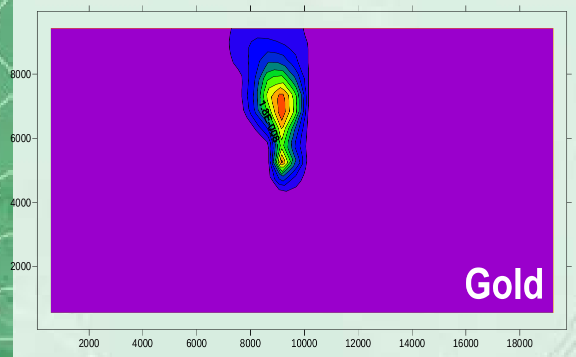


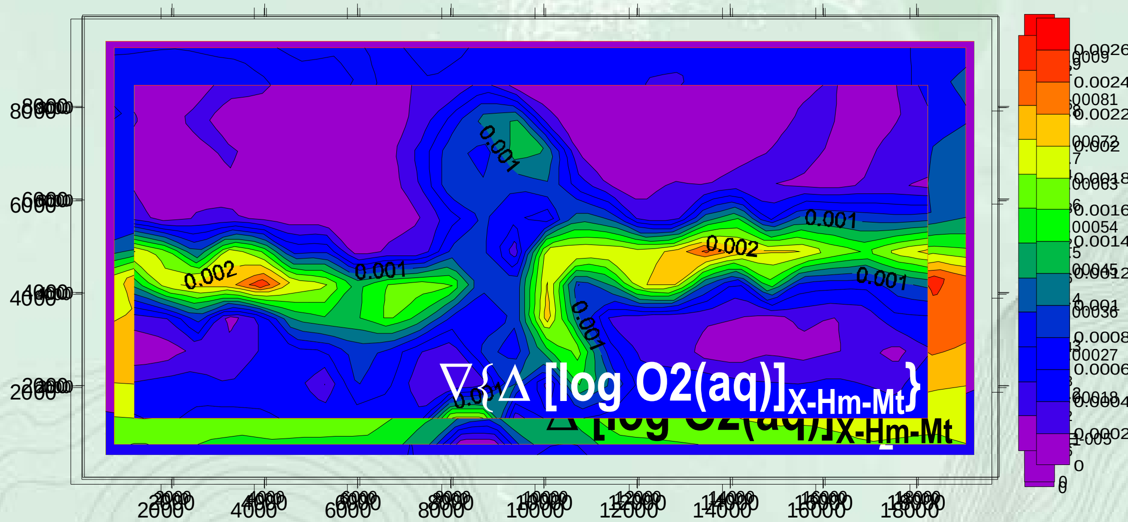


- **Upwelling plume has elevated ∇P and ∇T and correlates with gold**
  - –**Which is more important?**
    - •**Consider ∂Au/ ∂P and ∂Au/ ∂T**
  - –**What about chemistry?**



Spatial Gradients in T, P & C





- **Gold solubility in model dominated by $AuHS_{(aq)}$:**

$$Au(HS) + 0.5H_2O \longrightarrow Au + H_2S + 0.25O_2$$

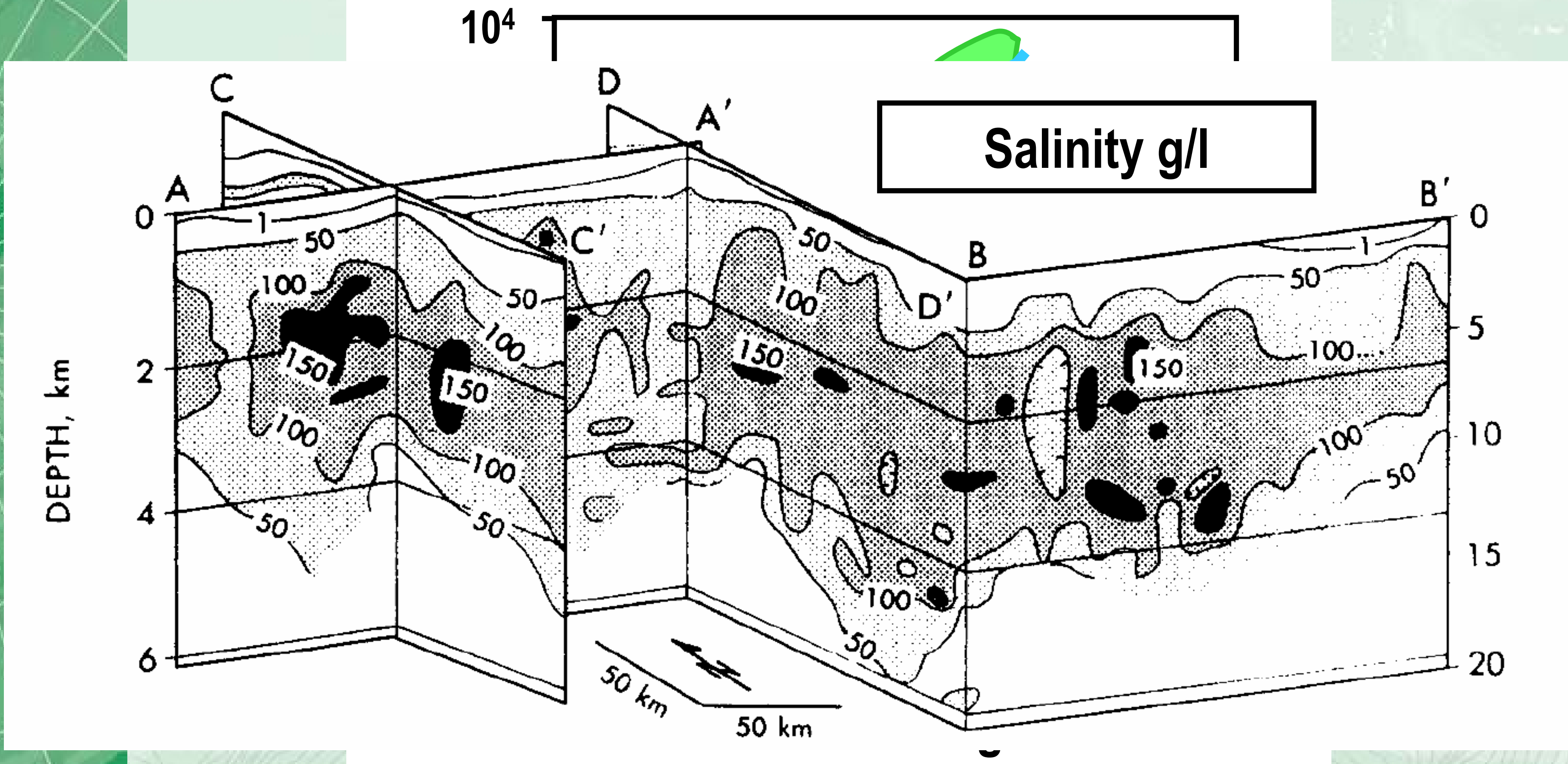
Spatial Gradients in T, P & C

Parameter	Spatial Gradient	Solubility Sensitivity	Spatial Sensitivity mol m^{-1}
Pressure	0.008 bar m^{-1}	7×10^{-12} mol bar^{-1}	5.6×10^{-14}
Temperature	0.026 °C m^{-1}	1×10^{-9} mol °C^{-1}	2.6×10^{-11}
H_2S	2.5×10^{-6} mol m^{-1}	2×10^{-4} mol mol^{-1}	5×10^{-10}
O_2	3×10^{-35} mol m^{-1}	1×10^{27} mol mol^{-1}	3×10^{-8}

$$Au(HS) + 0.5H_2O \rightarrow Au + H_2S + 0.25O_2$$

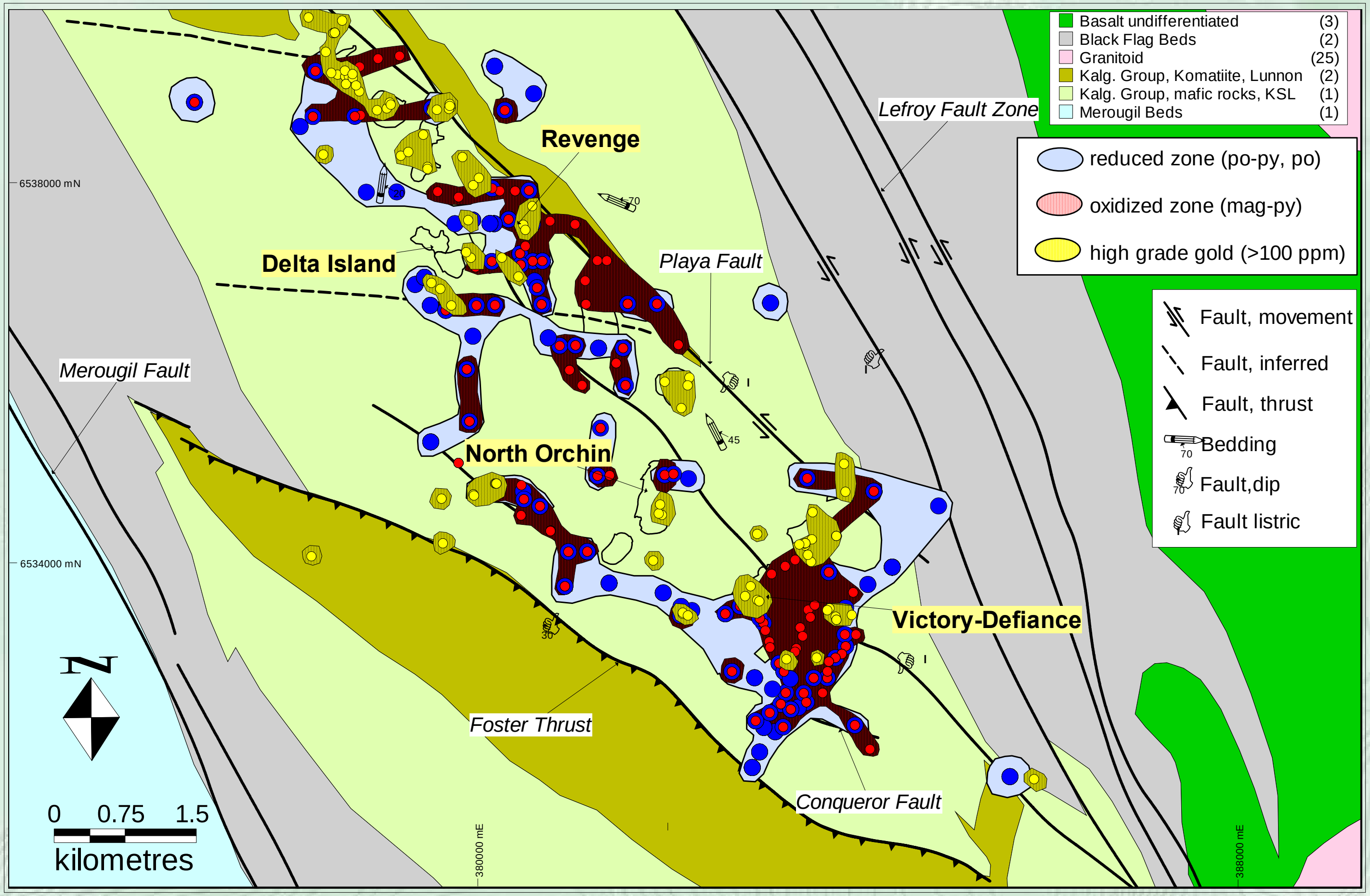
Real World Spatial Gradients

- **Gulf of Mexico, onshore Louisiana**



Hanor, 1994

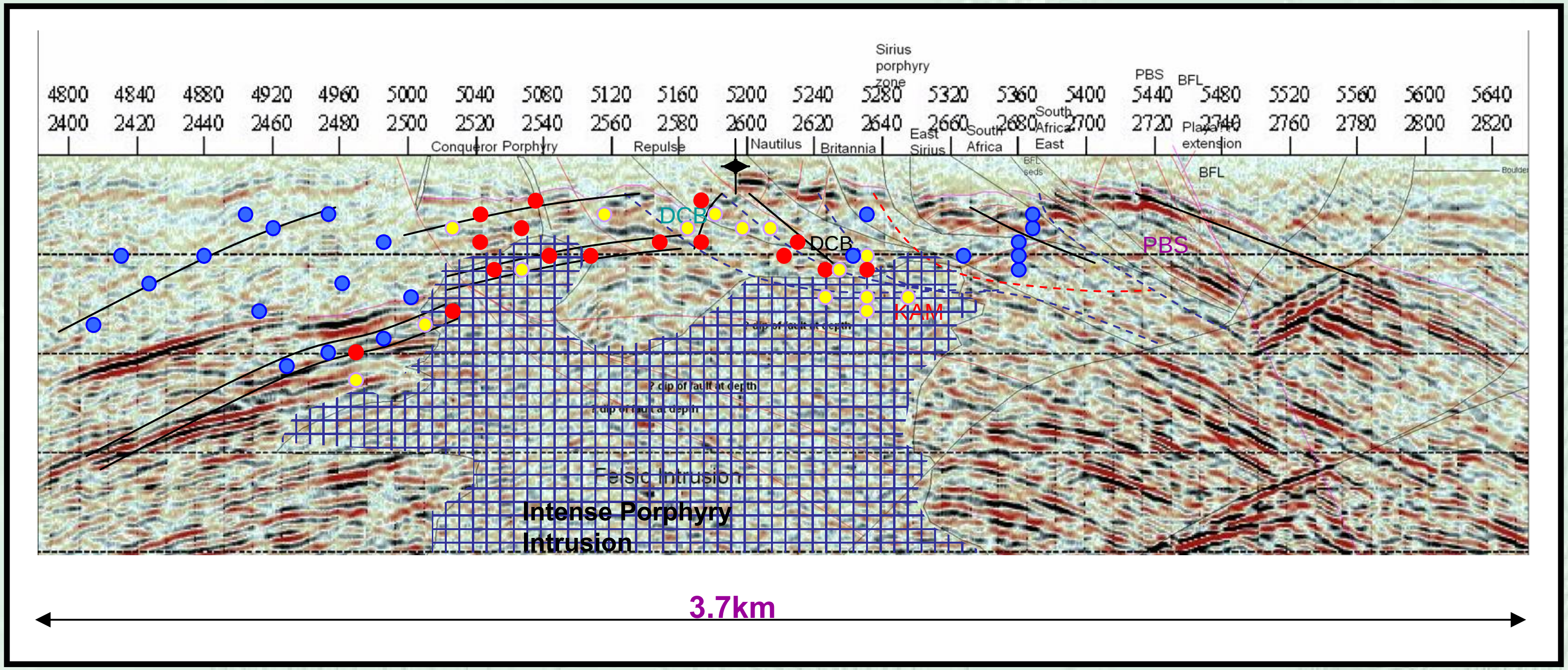
Real World Spatial Gradients



From Y3/Y4/MERIWA team

- **St Ives, Western Australia**

Real World Spatial Gradients



From Y3/Y4/MERIWA team

- **Redox state (coloured dots) varies with proximity to zone of intense porphyry intrusion**

B, D. Maximising Time….

Steep gradients in P, T (& X) are typically transient

Unless the location is…

- near surface *(T, P?, X?)*
- subject to repeated igneous activity *(T, X, P?)*
- experiences repeated breaching and healing of seal *(P)*
- undergoes repeated deformation-induced dilation effects *(P)*
- possesses a stable hydrology *(X, P?, T?)*

How is This Relevant to Exploration?

- **Provides an alternative view of critical parameters for ore formation**
  - **Gradient in hydraulic potential**
  - **Permeability**
  - **Solubility sensitivity to P, T, C**
  - **Spatial gradient of P, T, C**
  - **Timing & duration**

Fluid Sources

- **How many are significant?**
- **Perhaps only 2:**
  - **Meteoric**
    - which may be extensively modified
  - **Magmatic**
    - which may be H_2O, CO_2, NaCl or perhaps CH_4 rich
- **These will only be active at certain times**
  - **Isa Inlier Cu: D3 timing indicated**

- Meteoric fluids, driven by sub-aerial topography with deep penetration facilitated by faults
- A kt CO_2/day from Yellowstone (~60%
r
- Anthropogenic emissions ~20 Mt/d

Risking

- This analysis yields explicitly *necessary and sufficient* independent parameters suited to use in Bayesian risk analysis

$$P = P_1 \times P_2 \times P_3 \times P_4 \ldots$$

(c.f. Lord et al., 2001)

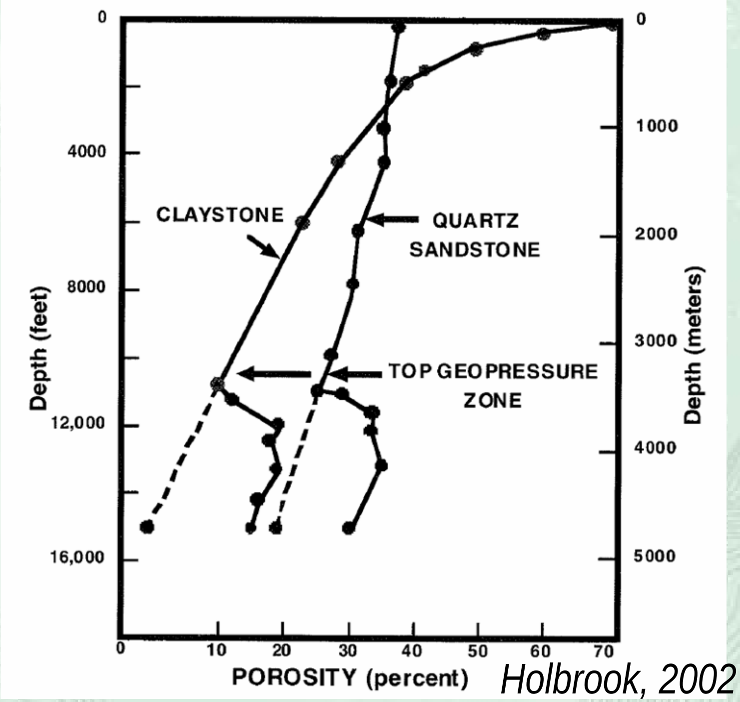
- Not based on specific processes for any one system

Some Lessons

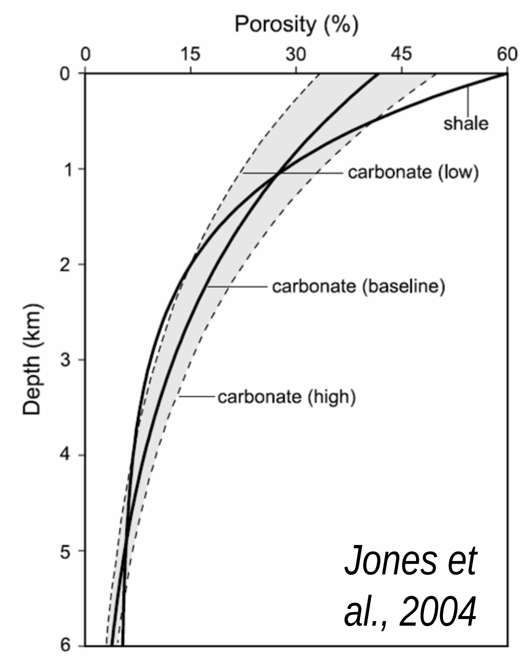
- **Role of reactivation and other inherited architectures (facies & permeability potential)**
- **There are less variables than at first glance – fluids available only at certain times**

Further Lessons

- **Much information already exists on the behaviour of basinal systems**
- **We must use it!**

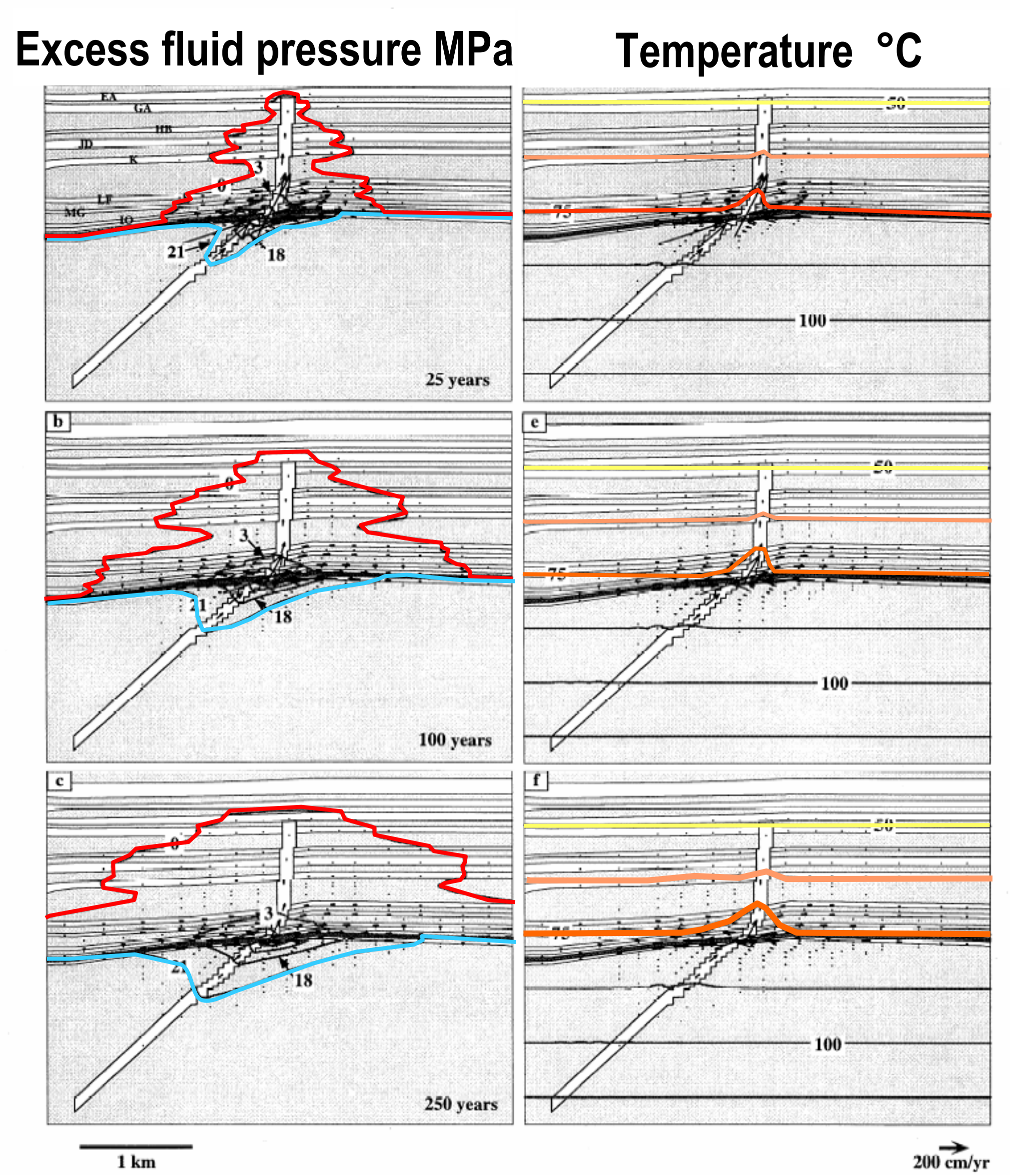


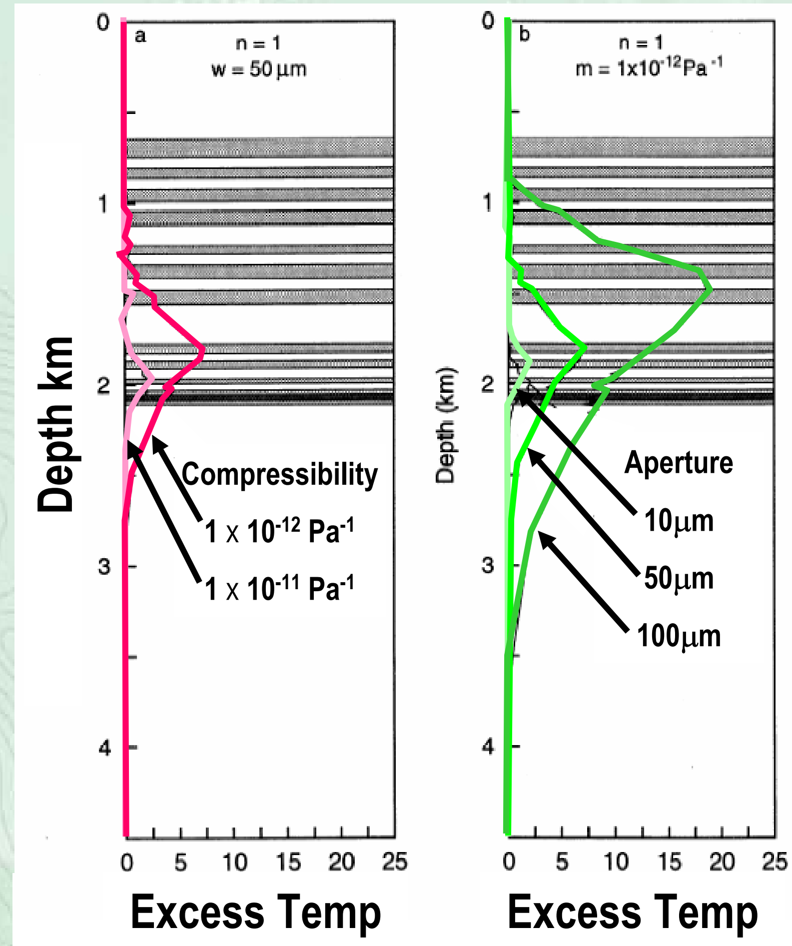
Holbrook, 2002



Jones et al., 2004

Permeability Evolution





- **Fault permeability varies with fluid pressure**

Roberts et al., 1996

In Summary…..

$$\text{Amount of mineral} = \int \frac{k\rho g}{\mu} \cdot \text{Hydraulic Gradient} \cdot \sum \left(\text{Solubility sensitivities} \cdot \text{Spatial Gradients} \right) \cdot dt$$

- **Critical factors for forming a (giant) ore system:**
  - –**Gradient in hydraulic potential** DRIVER
  - –**Permeability** ARCHITECTURE; PATHWAY
  - –**Solubility Sensitivity** * !
  - –**Spatial gradient of P, T, X** ARCHITECTURE; DEPOSITION
  - –**Maximum duration** GEODYNAMICS

**This will be zero if an appropriate fluid is not present!*

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Another view of the 5 Questions

- **Geodynamics**
- **Architecture**
- **Reservoirs** controlled by
- **Flow paths and drivers** dependent on
- **Deposition** function of

This Means….

- **The processes of ore deposition are a culmination of normal earth processes – it is their coincidence that leads to mineralisation**
- **Effective understanding must be based on the** *geology of economic deposits*, **and** *not economic geology*