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PROJECT F2.

The Development of Conceptual Multiphase Hydrothermal and Magmatic Process Models for Reactive Transport in Deforming Fractured Rock Masses

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December 2002

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F2: The Development of Conceptual Multiphase Hydrothermal and Magmatic Process Models for Reactive Transport in Deforming Fractured Rock Masses

Project Leader: Bruce Hobbs
CSIRO Exploration and Mining

Other Participants: Nick Oliver JCU, John McLellan JCU, Alison Ord CSIRO, Chongbin Zhao CSIRO, Peter Alt-Epping CSIRO, Yanhua Zhang CSIRO

Program: Program 4, Fluids

Linkages: M2, M3, Program 1,A1, Integration Project

Commencement Date: 1 March, 2002

Project Duration: To 30 June, 2005

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How Does F2 Integrate with the Rest of the Modelling World?

F2 supplies analytical and numerical solutions and constraints to idealised problems that involve the fundamental processes involved in mineralising systems.

Modelling Project

- **M1** – Software Framework
- **M2** – Software to Test Real Scenarios
- **M3** – Applications and Training

Fluids Project

- **F2** – Analytical and Numerical Solutions to Idealised Problems

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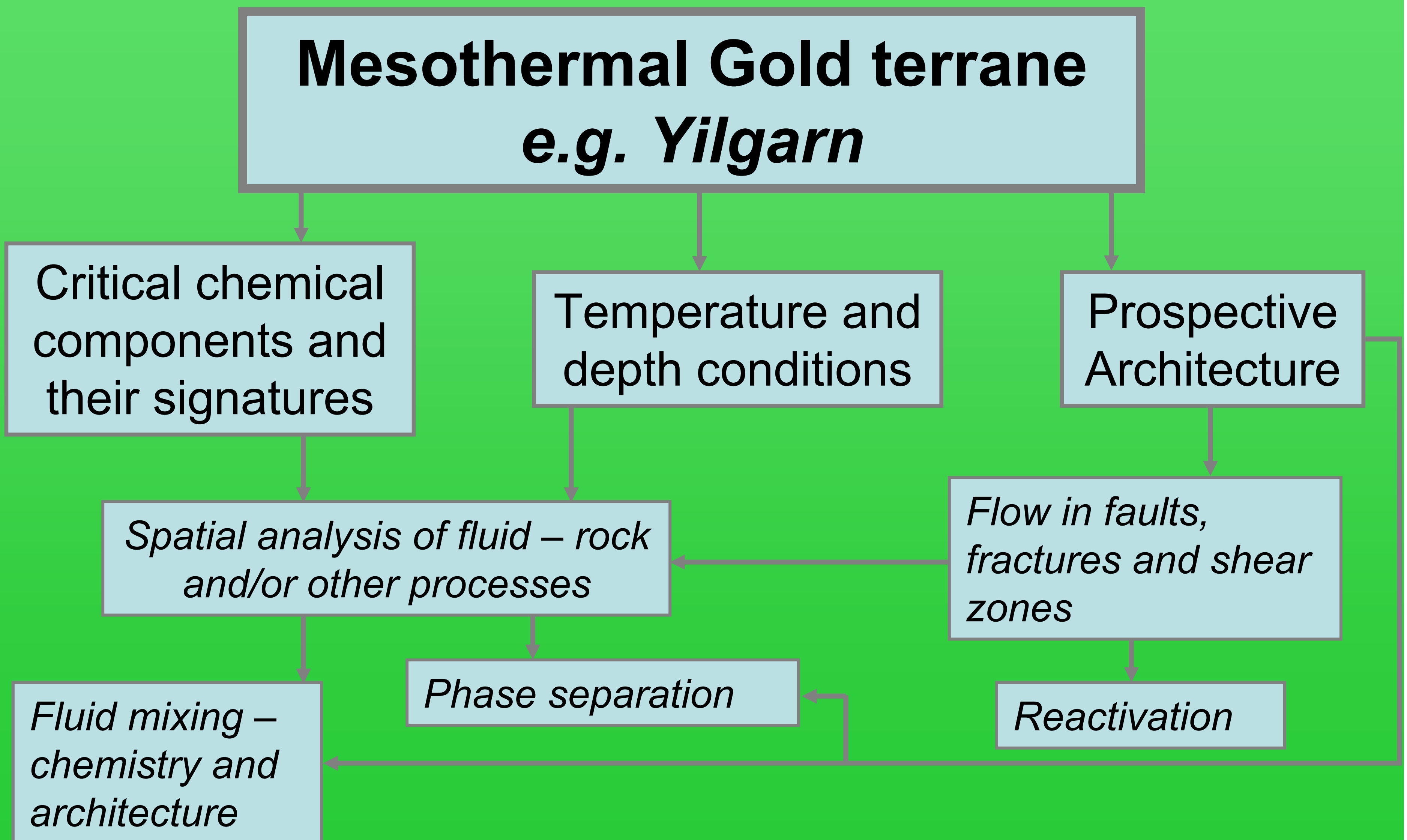
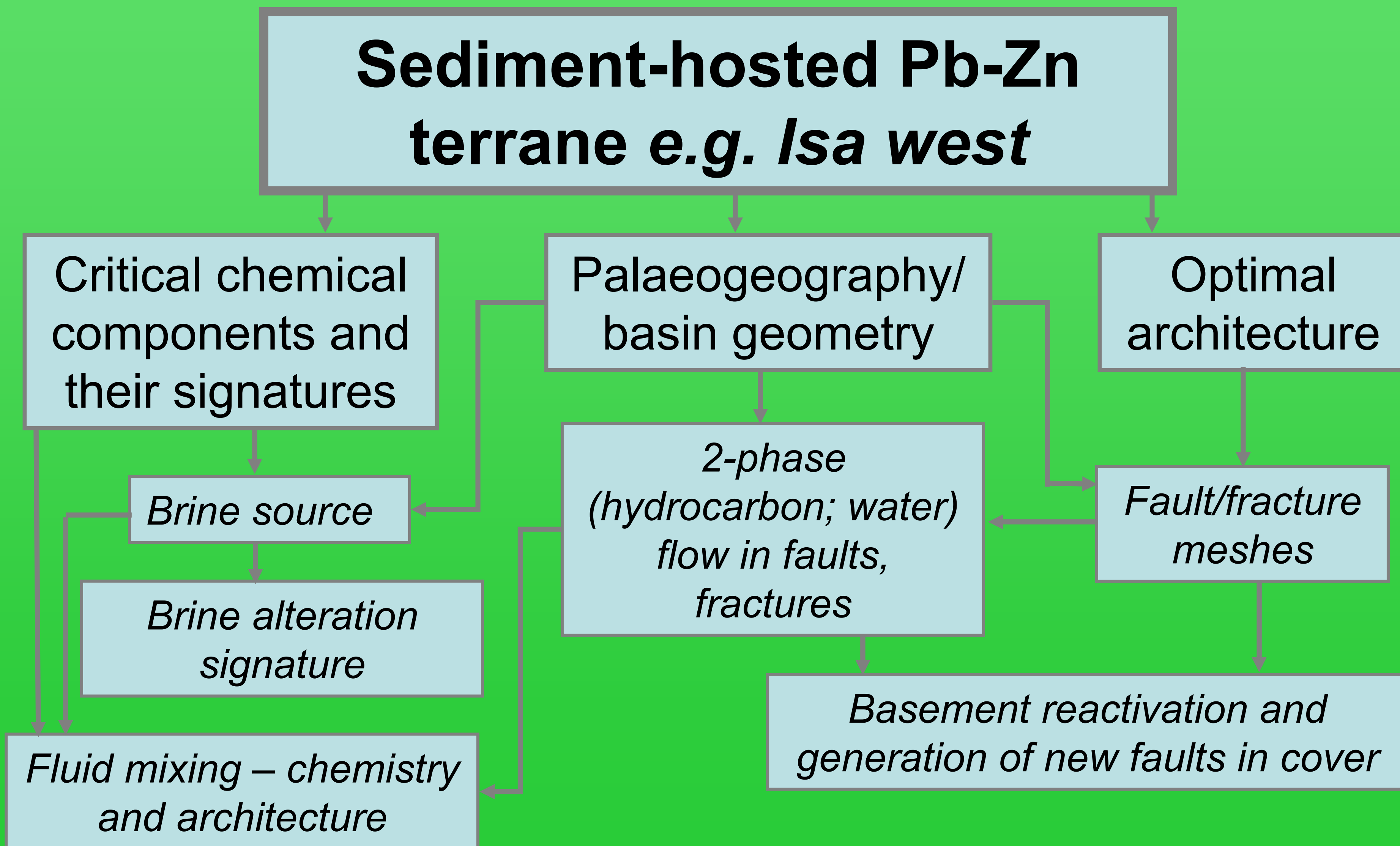
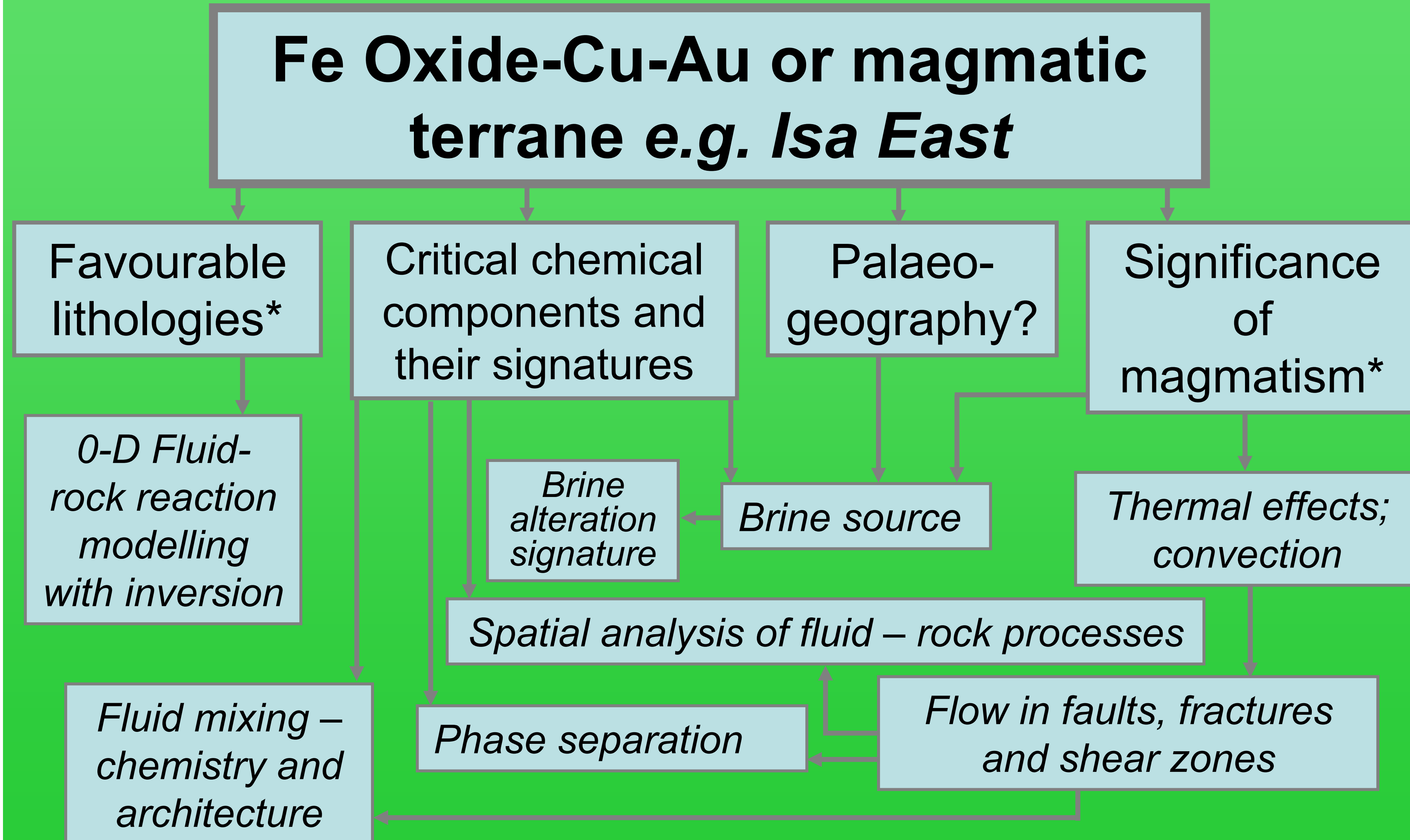
Mesothermal gold



Sediment-hosted Pb-Zn



Fe oxide-Cu-Au / magmatic



Not applicable in all cases

F2 Project Aim

To develop and generate new process models for geological processes critical to the modelling of mineralised systems, particularly fluid flow, thermal advection, fluid mixing and fluid/rock reaction.

These processes involve, in particular,

1. Porosity generation and destruction.
2. Phase separation and multi phase flow.
3. Magmatic processes.
4. Fluid flow in fractured rock masses.
5. Volume change due to chemical reaction.
6. The systematics of convection

How will F2 project outcomes will contribute to a fundamental shift in exploration practice? (1)

The basic premise of the pmd*CRC is that a shift, within the exploration community, towards quantitative thought experiments, involving the holistic mineralising system, will lead to more efficient targeting practices and hence greater probability of discovery.

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How will F2 project outcomes will contribute to a fundamental shift in exploration practice? (2)

The F2 project aims to develop a "text book" or "data set" of rigorous analytical solutions, accompanied by geologically realistic examples, of the fundamental processes that operate to generate world class ore bodies.

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How will F2 project outcomes will contribute to a fundamental shift in exploration practice? (3)

This “text book” enables explorationists to learn about processes, constrain their thinking and visualise the general solutions to problems before undertaking detailed computational modelling of specific examples (M2 and M3).

Progress against Plan

Deliverables

1. Porosity generation and destruction.
2. Phase separation and multi phase flow.
3. Magmatic processes.
4. Fluid flow in fractured rock masses.
5. Volume change due to chemical reaction.
6. The systematics of convection

Progress

1. Completed but specific applications need to be defined
2. Just begun – workshop in early 2003 – 2 phase flow available
3. Just begun – workshop in early 2003
4. Trials using ELFEN. No fluid coupling yet. Should have good progress by June 2003
5. Not started
6. Good progress – completion by June 2003

Major Highlights and Implications

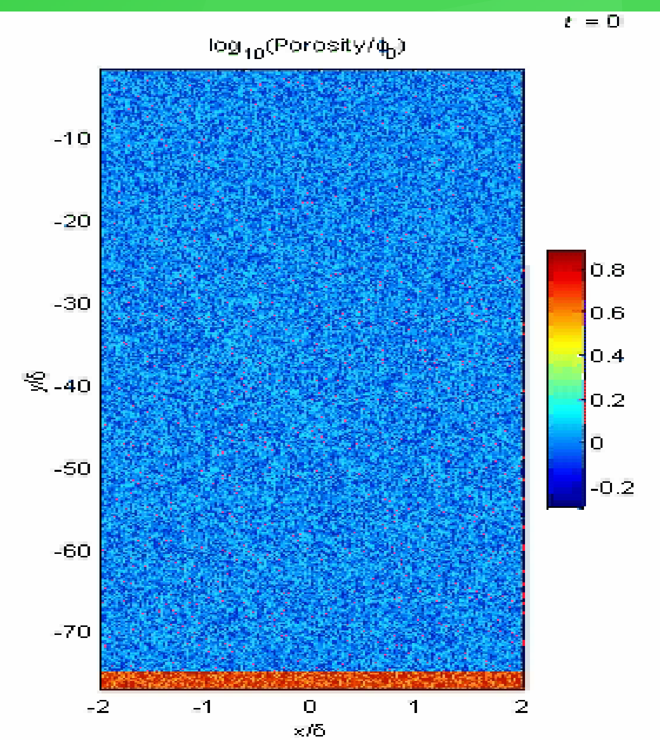
1. **POROSITY GENERATION AND DESTRUCTION.**

- **Kozeny-Carmen Equation is adequate to describe the quantitative effects: $K/K_o = A\,(\phi/\phi_o)^3$ where K is the permeability and ϕ is the porosity. A is a geometrical constant.**

pmd*CRC Major Highlights and Implications

1. POROSITY GENERATION AND DESTRUCTION. (cont)

- The porosity wave concept of Connolly is a powerful means of describing porosity evolution in compacting sedimentary basins and devolatilisation processes.



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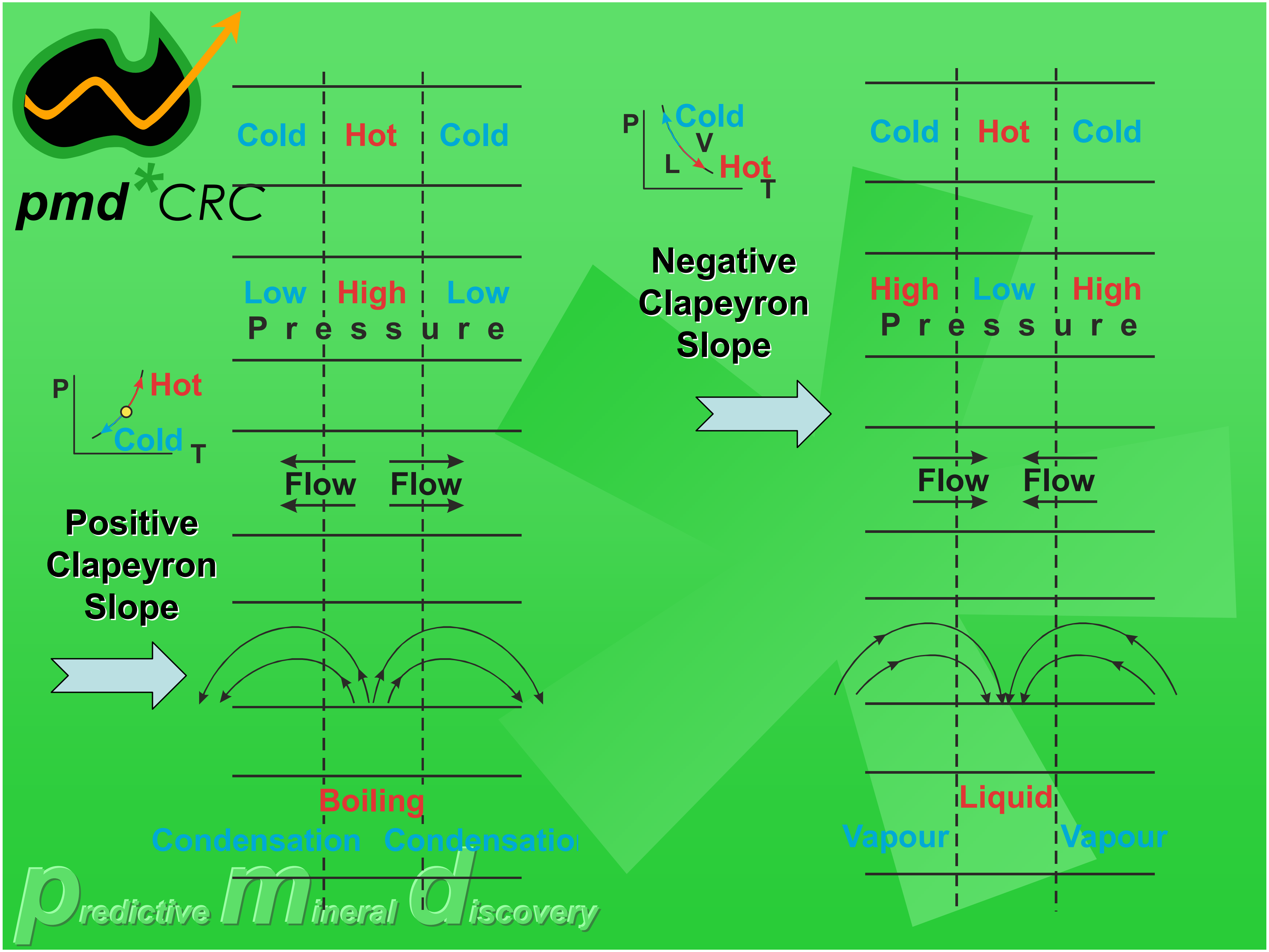
Major Highlights and Implication

2. PHASE SEPARATION AND MULTI-PHASE FLOW

- **Systematics of phase separation and multi-phase flow starting to emerge.**
- **Multi-phase flow (2D and 3D) now incorporated in FLAC.**
- **Convection in systems undergoing phase changes (eg boiling) is not driven by buoyancy but by pressure gradients induced by temperature variations. Phase change driven convection is concentrated towards the bottom of porous layers and the cells are finger like in aspect ratio.**



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Cold
Hot
Cold
Low
High
Low
Pressure
P
Hot
Cold
T
Positive Clapeyron Slope
Flow
Flow
Boiling
Condensation
Condensation
P
Cold
V
L
Hot
T
Negative Clapeyron Slope
Cold
Hot
Cold
High
Low
High
Pressure
Flow
Flow
Liquid
Vapour
Vapour
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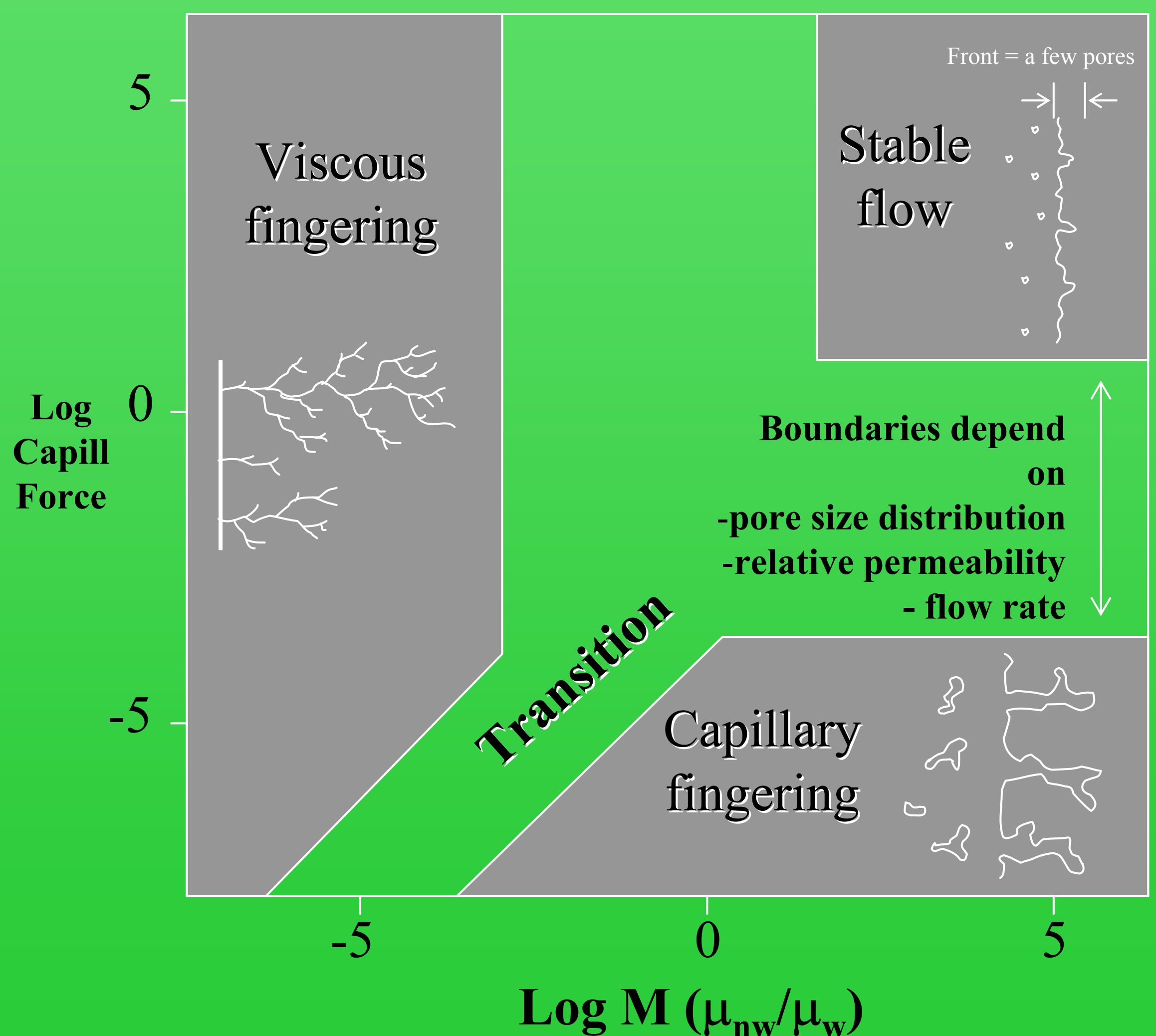
General two-phase flow behaviour in porous media

(Modified after Lenormand et al, 1988)



Multi-phase flow in heterogenous media very important but poorly understood

Boundaries uncertain – inconsistent with other published work

Transition ranges several orders of magnitude

Gravity & inertia neglected

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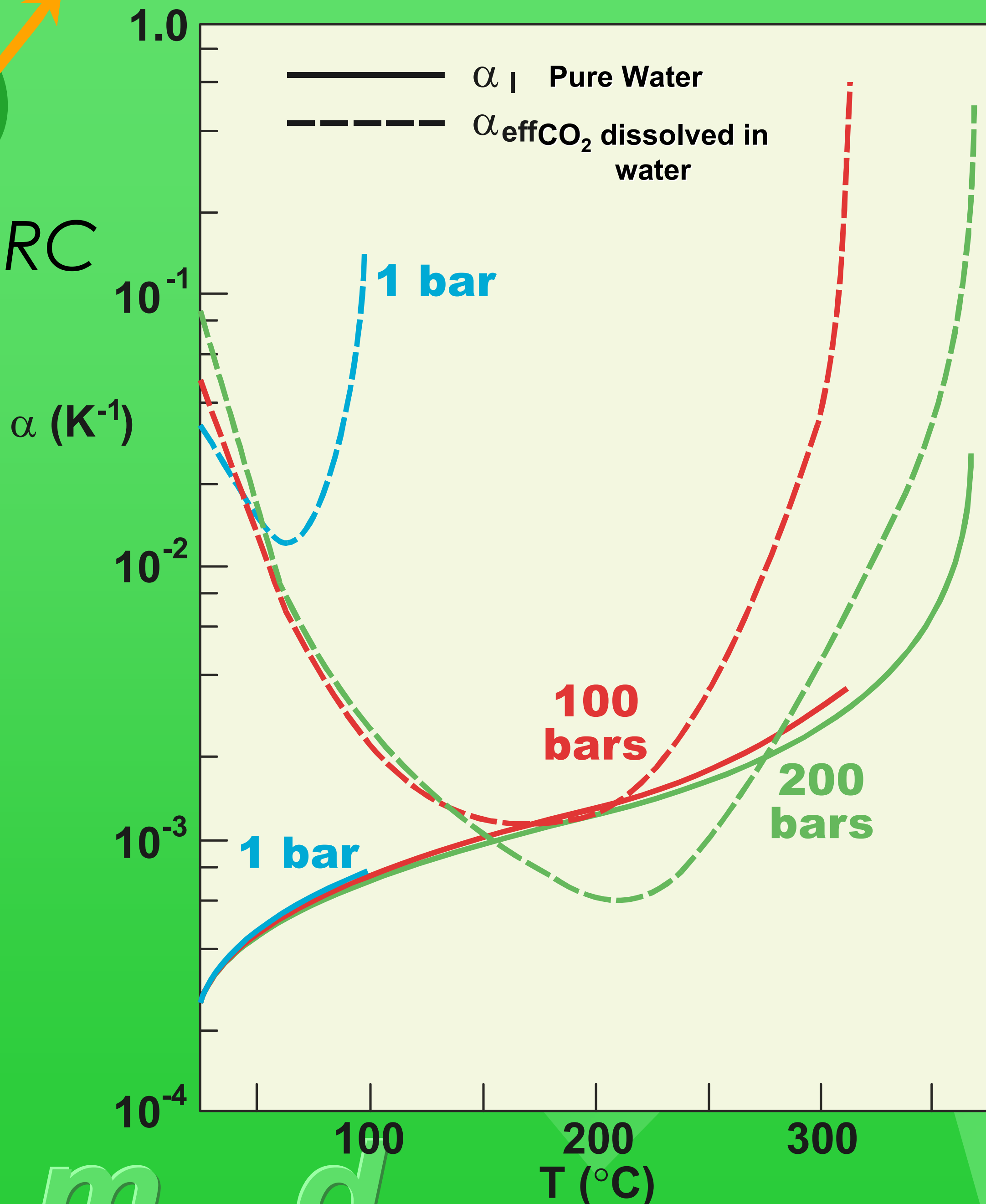
Major Highlights and Implications

2. PHASE SEPARATION AND MULTI-PHASE FLOW

- Solution and exsolution of CO_2 from an aqueous phase results in convection driven by buoyancy but the density changes are greater than in the Boussinesq approximation.
- The presence of CO_2 acts to greatly enhance convection at depths less than about 750 m. At greater depths CO_2 acts to inhibit convection at low temperatures but to enhance convection at high temperatures. The influence of CO_2 therefore depends upon the geothermal gradient.



Thermal expansion coefficient, α, for pure water (solid lines) and CO_2-water solutions (dashed lines).

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Major Highlights and Implications

3. ADVECTION OF HEAT

- Advection of heat (2D and 3D) now available in FLAC and Fastflo.
- Systematics of convection now established in 2D and 3D and in narrow faults.

Project Review 3-4 Dec. 2002, Canberra

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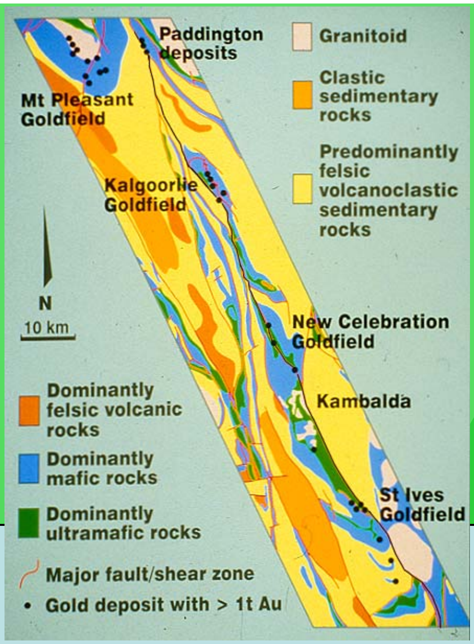

Major Highlights and Implications

3. ADVECTION OF HEAT

- Shape of convection cells changes from a simple cell at the critical Rayleigh Number, R ($4\pi^2$ in 2D and $4.5\pi^2$ in 3D) to finger shaped cells at higher values of R. Fingers narrow as R increases. Temporal oscillations in temperature begin at R=380 in 2D and R=575 in 3D. The route to chaos (R=850 in 2D and R=725 in 3D) is not a period doubling sequence but is punctuated with well defined periodic windows.

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Major Highlights and Implications

3. ADVECTION OF HEAT (CONTINUED)

The Rayleigh Number (which is a measure of the vigour of convection) is given by

$$R = \{ \alpha\ g\ \rho^2\ K\ \mathrm{grad}T\ H \} / \mu\ k$$

For a geothermal gradient of 25 K per km, over 10 km depth,

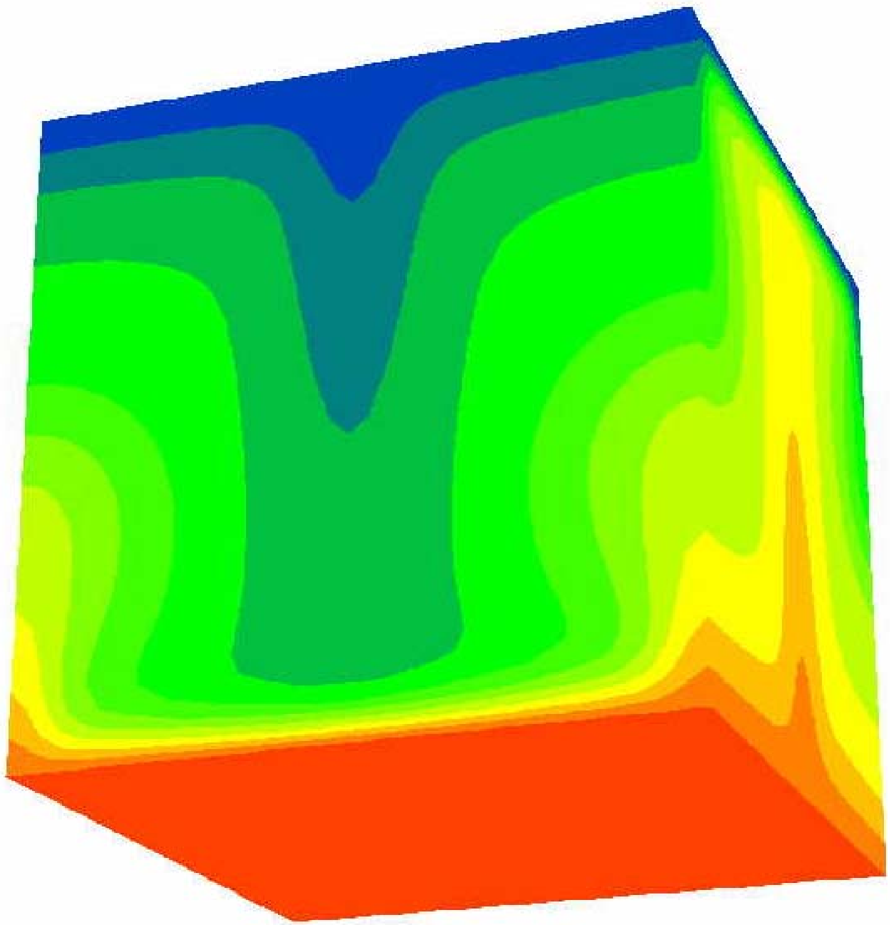
α : **Thermal Expansion, increases by 10**

ρ: **Density, decreases to 900 kg/m^3**

μ: **Viscosity, decreases by an order of magnitude.**

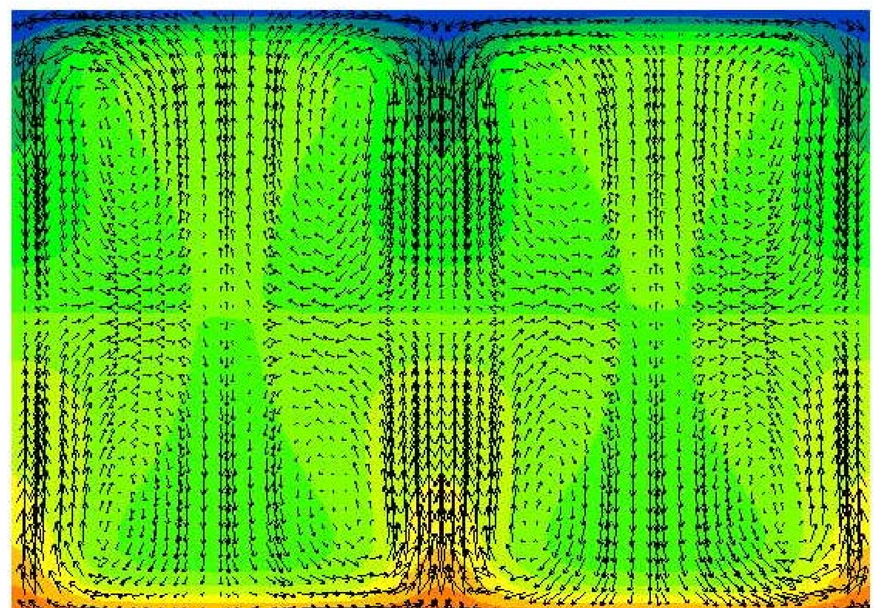
Critical Rayleigh Number can be reduced by 30.

It is therefore essential to take account of temperature and pressure dependent thermodynamic and transport properties in modelling the advection and convection of heat. In particular, at high geothermal gradients, the Boussinesq approximation is not applicable. These modifications need to be made to what we now have available.



Three dimensional convection in a porous medium – FLAC3D

Rayleigh Number 435



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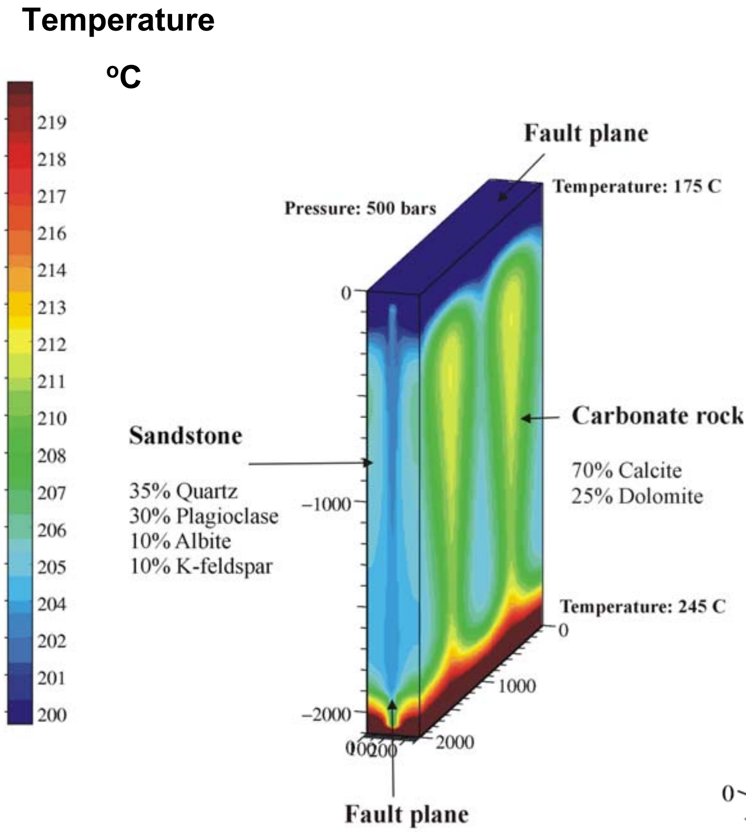
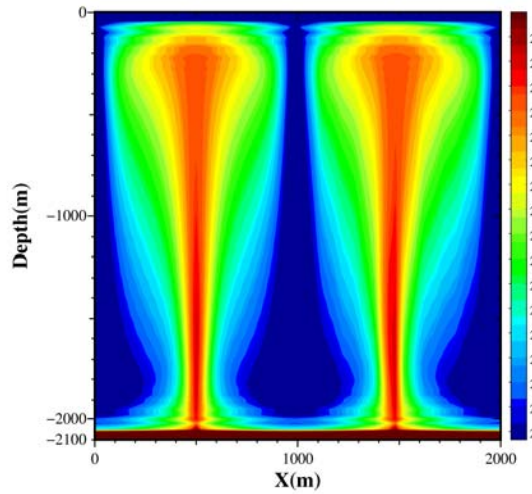
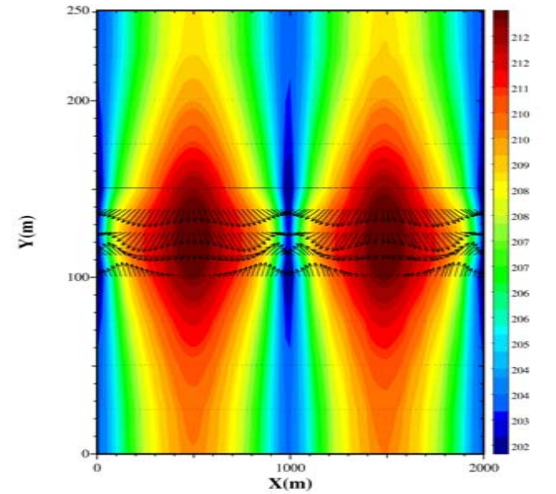
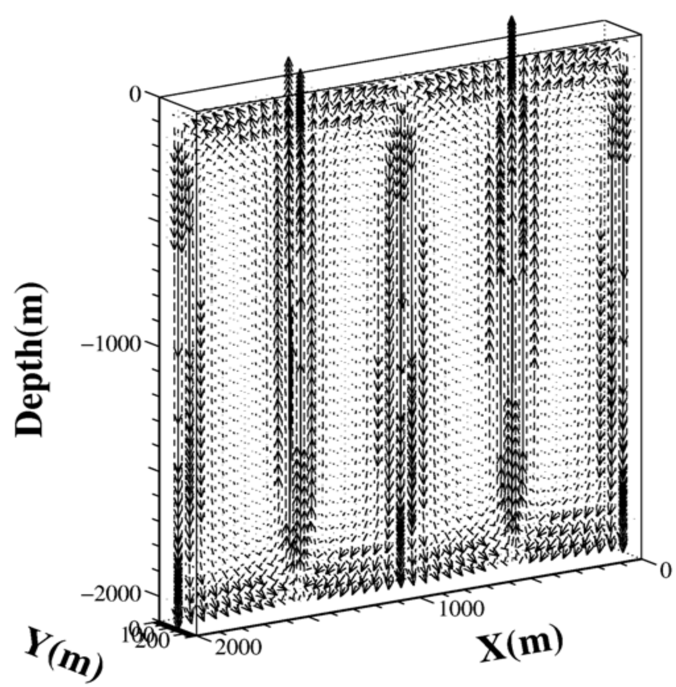


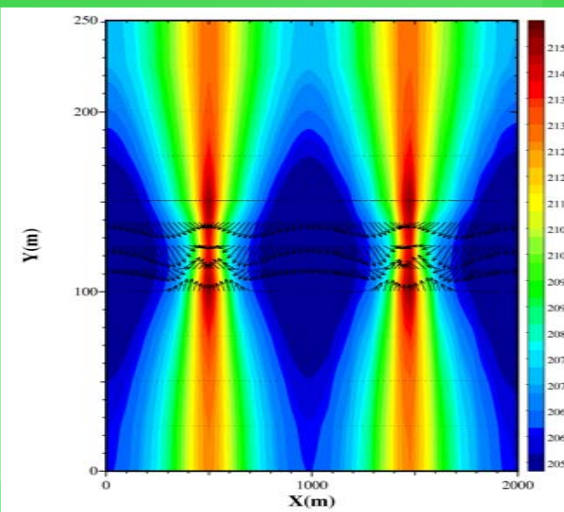




Vertical section parallel to fault

Horizontal section at depth of 250 m

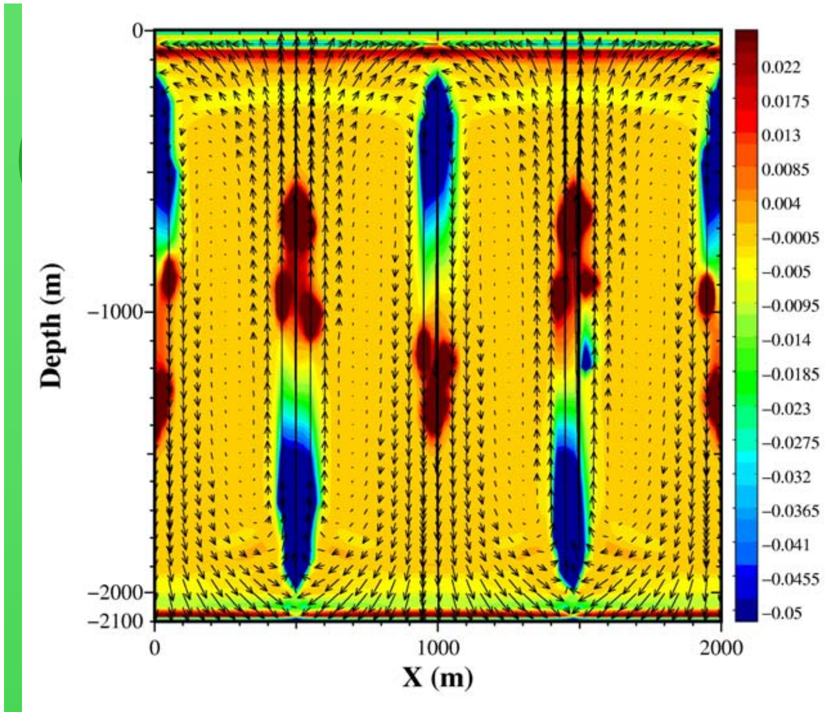


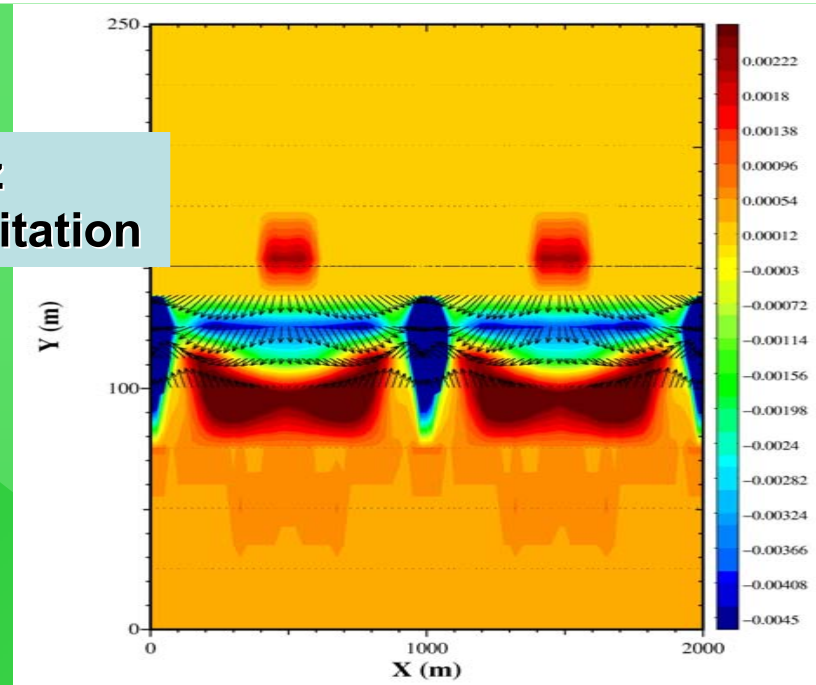


Horizontal section at depth of 1825 m

Modelling by Peter Alt-Epping

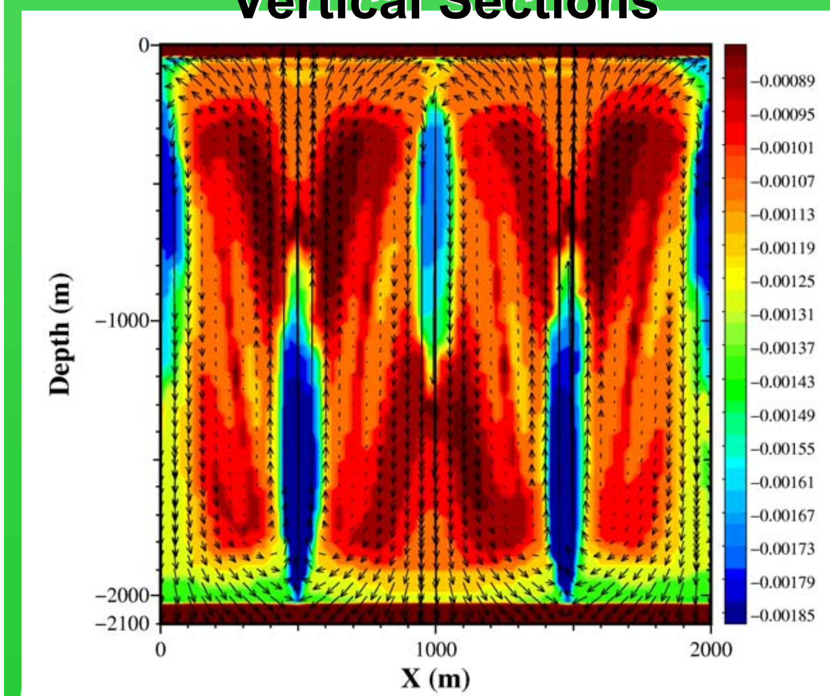
Quartz Precipitation

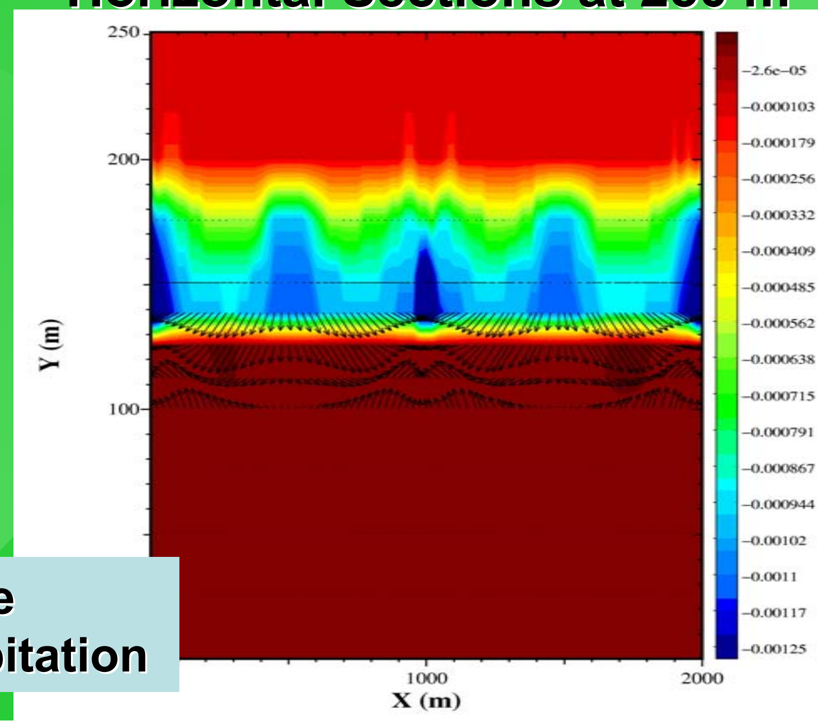




Vertical Sections

Horizontal Sections at 250 m

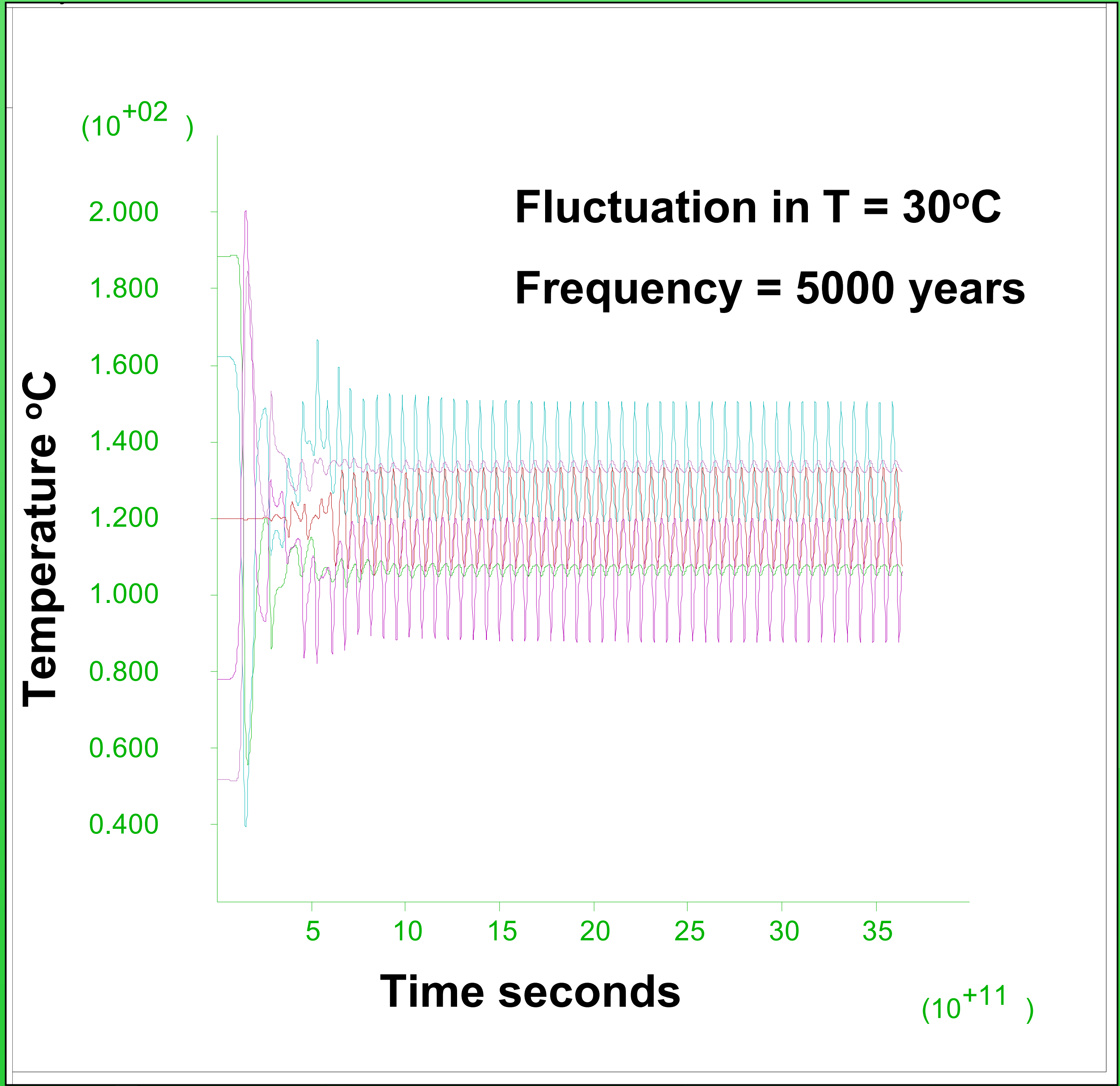




Calcite Precipitation

Temperature Oscillations at Rayleigh Number 1361

Application to zoning in sphalerites in Mississippi Valley Deposits?



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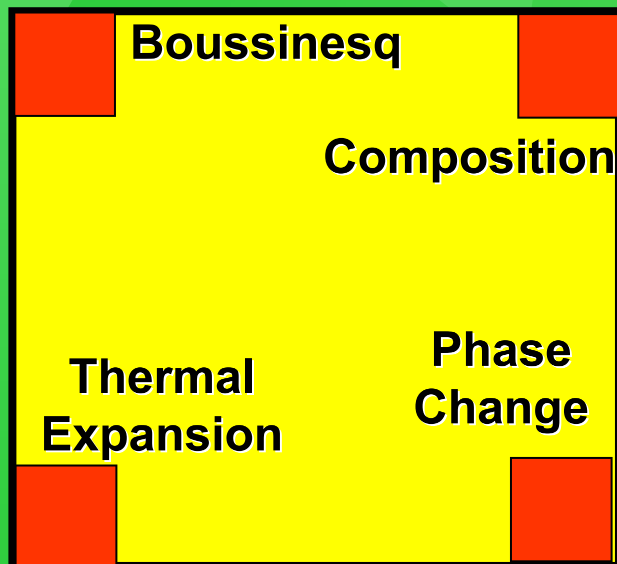
The Four Types of Convection

Classical Boussinesq Approximation – Small Density Changes Due to Thermal Expansion

Thermo-haline Convection Due to Large Density Contrasts Arising from Compositional Changes



Convection Driven by Large Density Changes Arising from Thermal Expansion-CO_2 at High Temperatures

Phase Change Convection – eg Boiling. Positive Clapeyron Slope Drives Convection; Negative Slope Inhibits Convection

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Key Project Issues

- Will the project be finished on time? **YES**
- Are resources appropriate? **YES**
- Will it achieve its objectives? **YES**
- Any issues concerning collaboration and linkages with other projects? **BETTER INTEGRATION IS NEEDED WITH TERRAIN AND 1:1 PROJECTS**
- Any issues that have a bearing on the successful completion of the project need to be mentioned?

  THERE IS A PROBLEM IN ACCESS TO SUITABLE STAFF. THIS PROBLEM IS EXACERBATED BY THE LACK OF OPPORTUNITY TO OFFER ANY STABILITY IN THE APPOINTMENT.

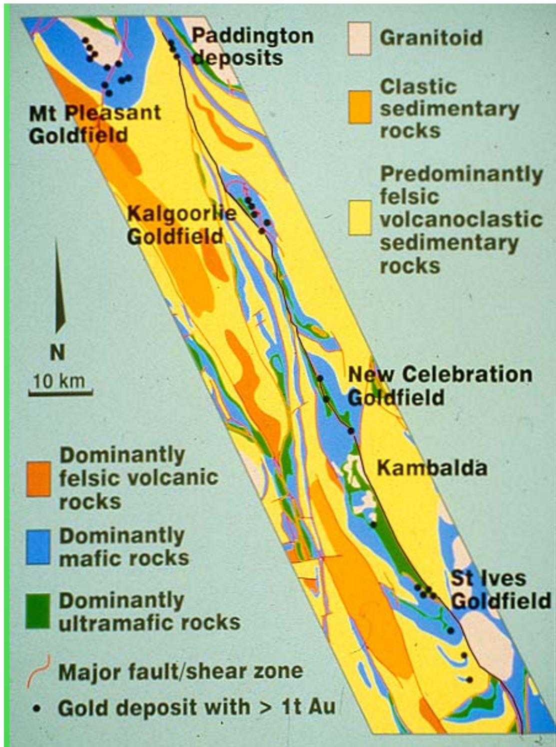
Future Directions

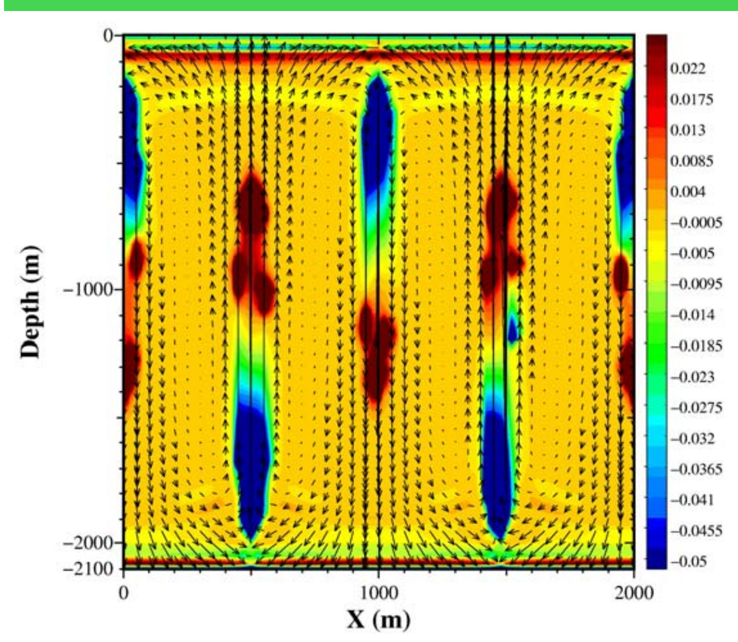
- Where do you see the project going after 30 June 2003?

  THE PROJECT WILL NEED UNTIL JUNE 2005 FOR SUCCESSFUL COMPLETION.

- How will it evolve and help the CRC achieve its vision?

  BY JUNE 2003 THE FIRST INTERACTIVE WORK SESSIONS WILL BE AVAILABLE TO ENABLE EXPLORATIONISTS AND STUDENTS TO EXPLORE “WHAT IF” SCENARIOS FOR A RANGE OF IMPORTANT MINERALISING PROCESSES, PARTICULARLY THOSE INVOLVING ADVECTION OF HEAT AND PHASE CHANGE/PHASE SEPARATION COUPLED WITH DEFORMATION. AT LEAST ANOTHER YEAR WILL BE REQUIRED TO BRING THE COMPLETE STABLE OF PROCESSES INTO THIS INTERACTIVE SYSTEM.





Thank you.

Perhaps as an indication of the use of understanding the systematics of mineralising processes, one could consider the Kalgoorlie region again.

The theory says that if the periodicity of mineralisation is due to convection, the cells would have to be a minimum of 20 km high and the Rayleigh Number (ca.3000) would then predict other patterns.

However, if one thinks of this in terms of convection fingers then the period of mineralisation could be much smaller. Then, other mineral deposits would be present but at depth as shown to the left.

A systematic look at alteration patterns along the fault would enable predictions to be made.