Reactive Transport Modeling Approach to Studying Silicification of Carbonates*

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Abstract

Reactive transport models provide a systematic approach to evaluate diagenetic processes in terms of fluid flow, heat transport and reactions along flow paths, in complex geologic systems. We present a case study where reactive transport modeling was used to investigate the silicification of a carbonate buildup. Our modeling workflow consists of three steps of progressively increasing complexity: single cell “batch” experiments were used to evaluate the diagenetic potential of several combinations of fluids and lithologies; then, the most favorable fluids were applied in column experiments to test the fundamental controls on the process of calcite replacement by silica; finally, the spatial and temporal distribution of silicification of a carbonate build-up was simulated under four different flow regimes, in cross-sectional models.

Our findings show that conditions that favor replacement of carbonate by silica include: (1) the interaction of fluids and volcanic rocks to produce silica-rich fluids, (2) high concentrations of CO_2 to drive calcite dissolution, (3) an elevated geothermal gradient to transport fluids and heat, (4) rapid flow, for example through faults, (5) cooling, for example by entrained surface water, and (6) the occurrence of silica in the original sediments. We found that massive and pervasive silicification of a carbonate formation is difficult because the common parameter space for calcite dissolution and silica precipitation to occur is very narrow, which explains the relative paucity of large-scale carbonate silicification in natural settings.

Reactive Transport Modeling approach to studying silicification of carbonates

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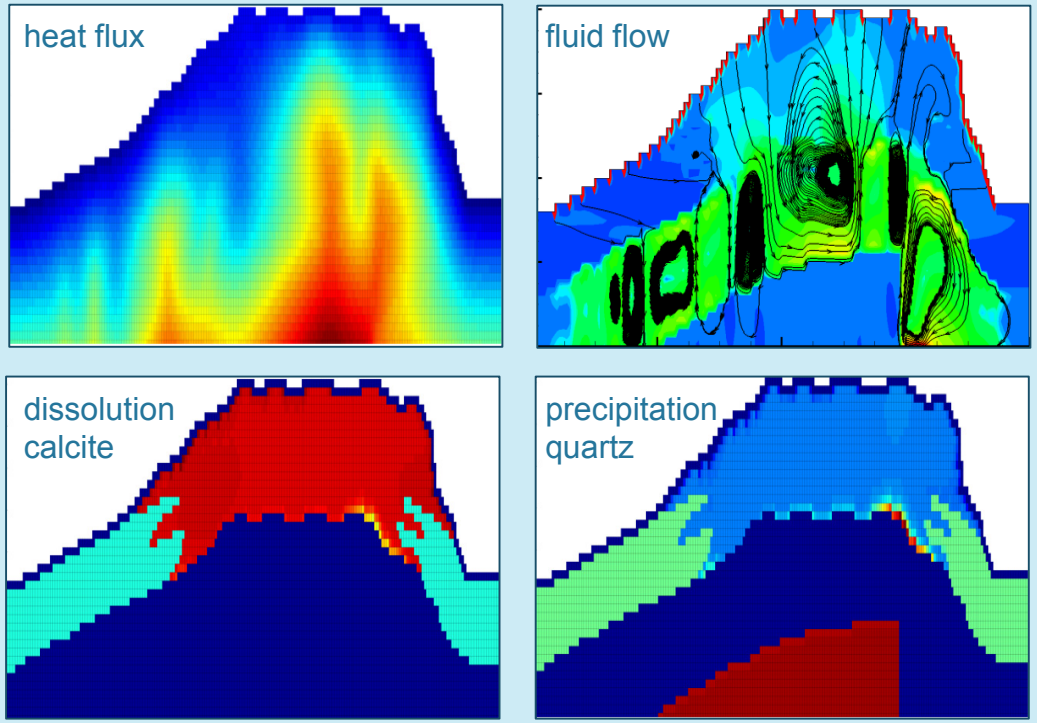
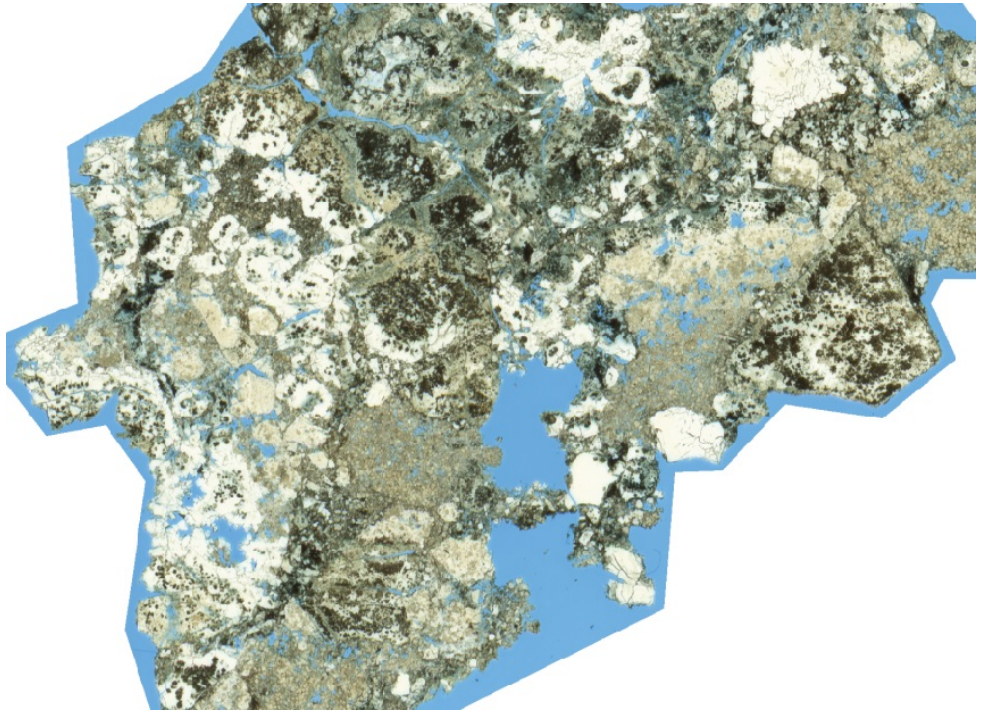
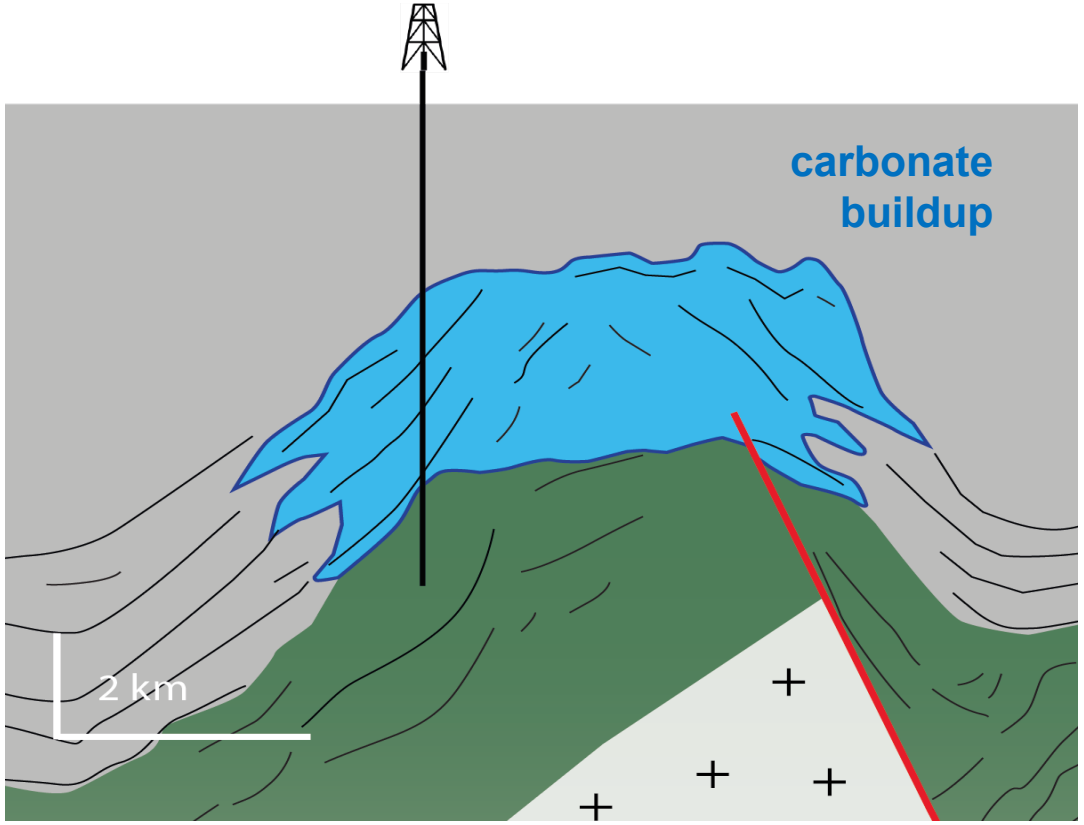
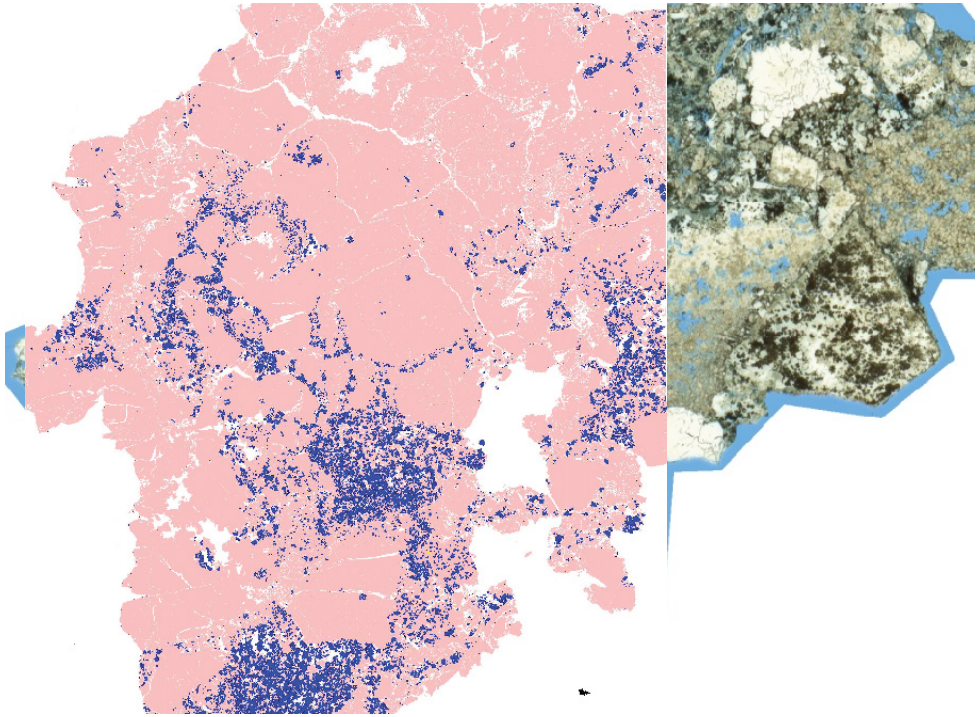




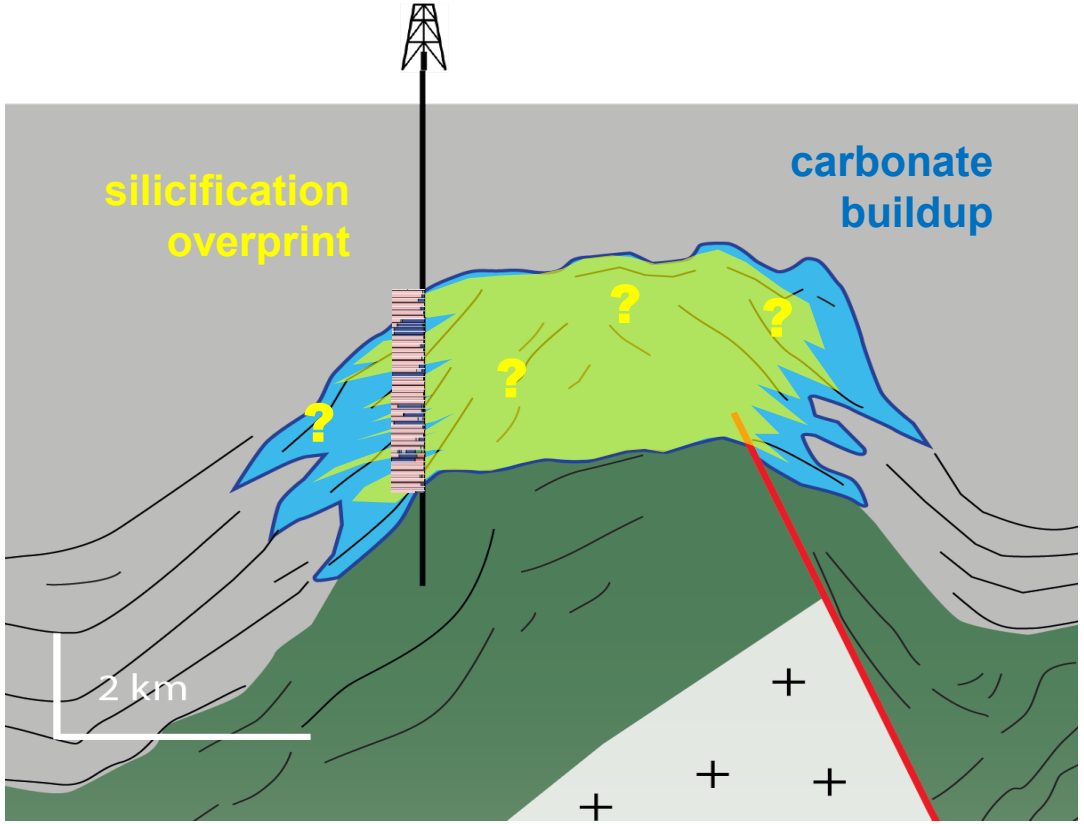
Transmitted light microscopy





QemScan mineralogy

	% area
Quartz	88.91
Dolomite	10.90

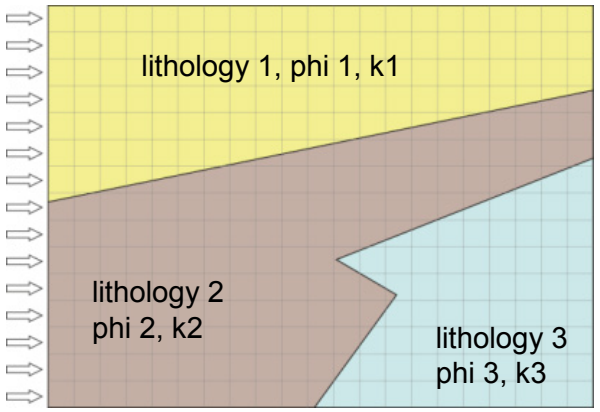


Study Goals

1. Carbonate-silica replacement process and impact on reservoir quality
2. Spatial distribution of silicification in carbonate buildups
3. Generic learnings for global exploration

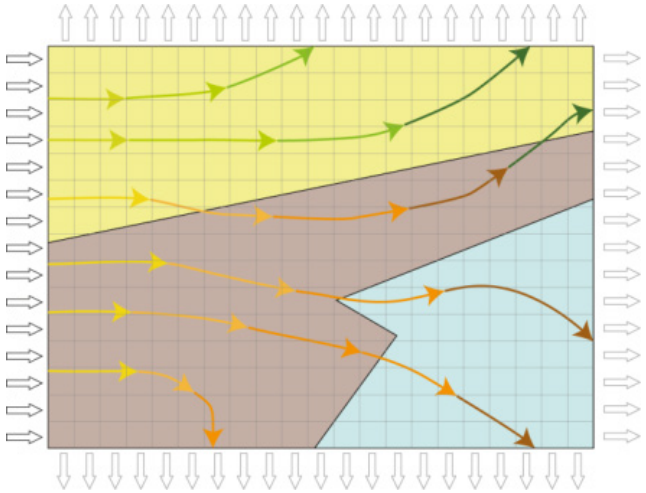
Reactive Transport Modeling

INPUT



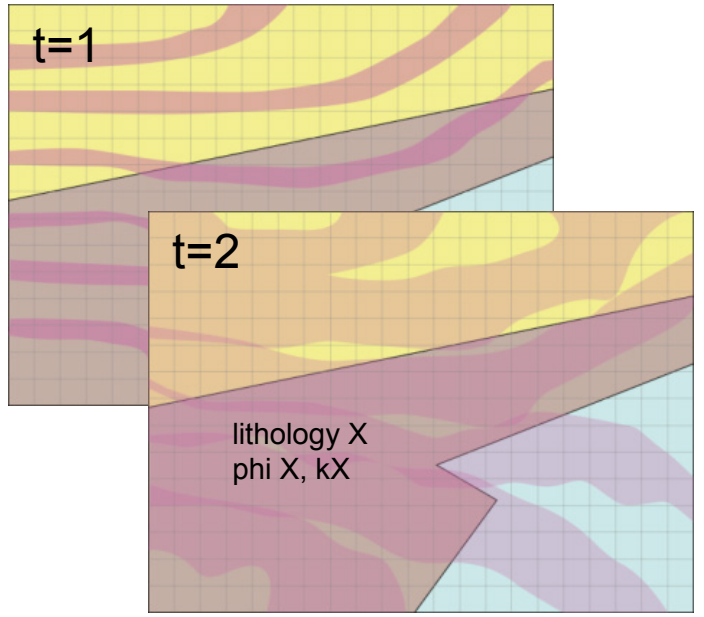
- Grid
- Rock properties
- Fluid properties
- Temperature, pressure
- Time

SIMULATION



- Flow
- Solute transport
- Chemical reactions (mineral dissolution and precipitation)

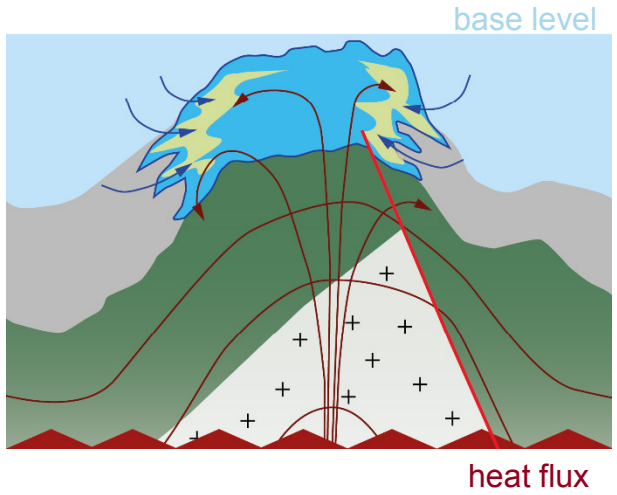
OUTPUTS



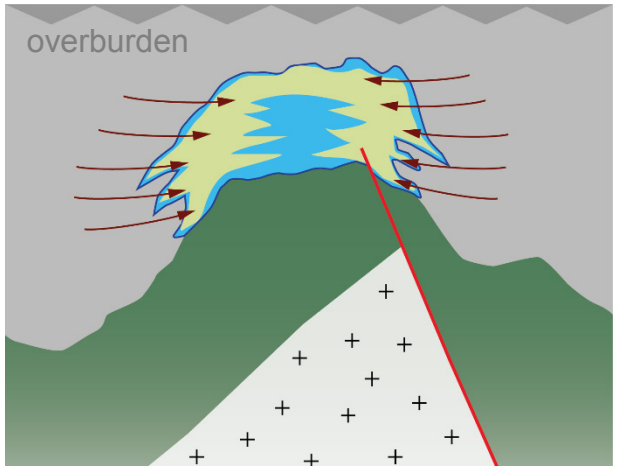
- Changes in rock properties
- Fluid evolution

Four conceptual models

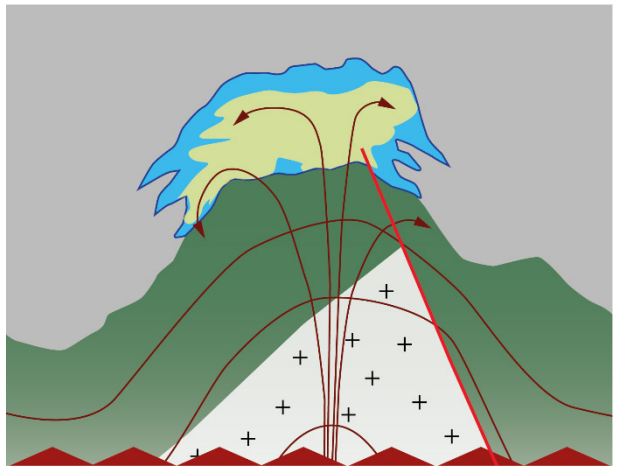
kohout circulation



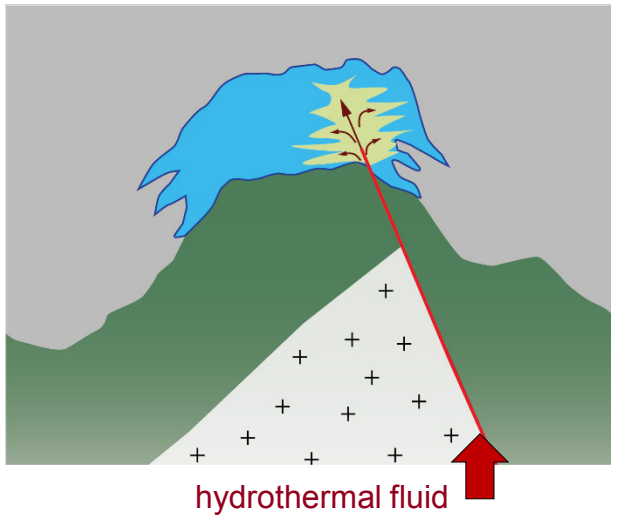
shale compaction



geothermal convection

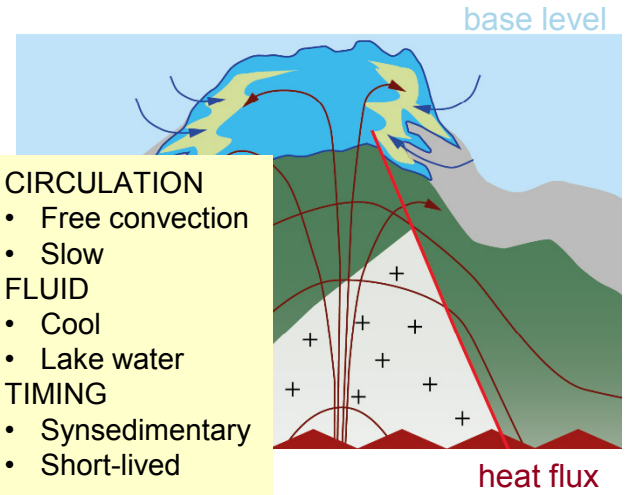


hydrothermal flow through faults



Four conceptual models

kohout circulation

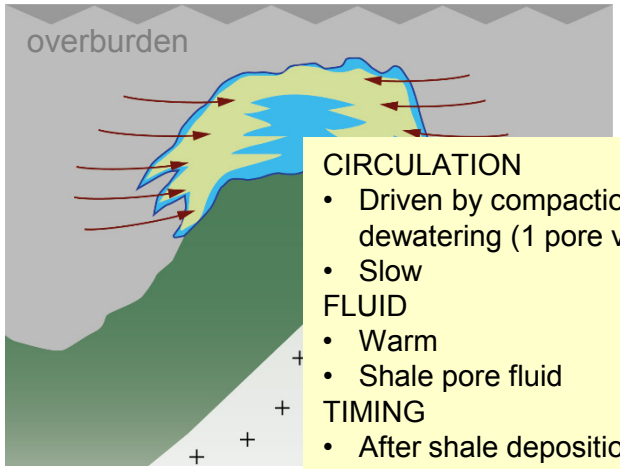


CIRCULATION
- Free convection
- Slow

FLUID
- Cool
- Lake water

TIMING
- Synsedimentary
- Short-lived

shale compaction

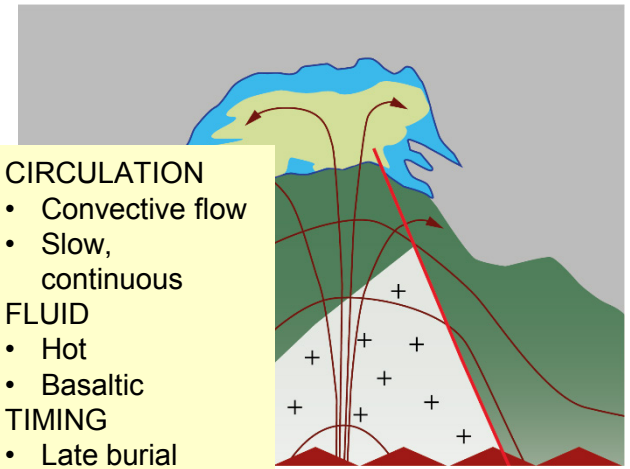


CIRCULATION
- Driven by compaction dewatering (1 pore vol)
- Slow

FLUID
- Warm
- Shale pore fluid

TIMING
- After shale deposition
- Long-lived?

geothermal convection

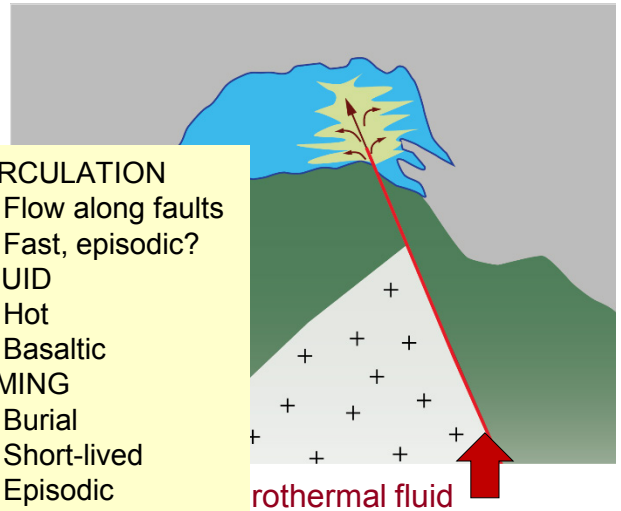


CIRCULATION
- Convective flow
- Slow, continuous

FLUID
- Hot
- Basaltic

TIMING
- Late burial
- Long-lived
- Episodic?

hydrothermal flow through faults

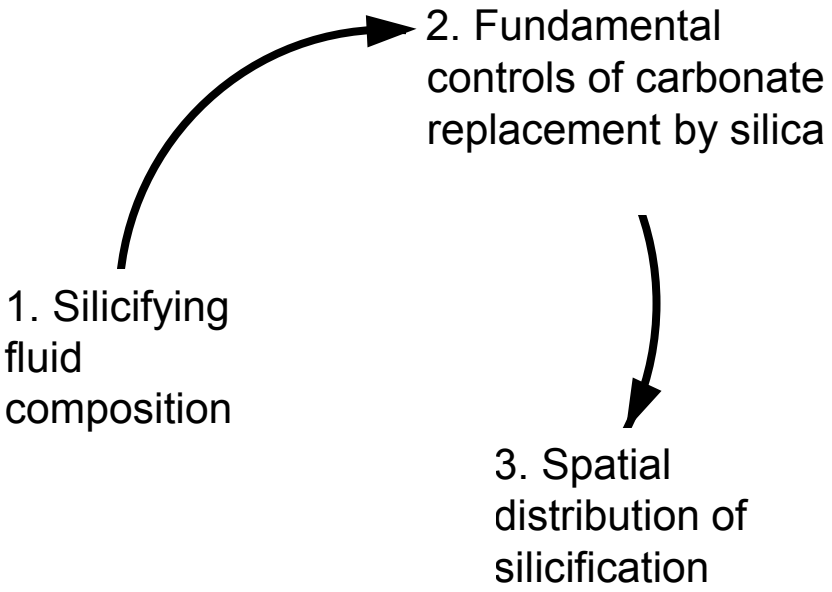


CIRCULATION
- Flow along faults
- Fast, episodic?

FLUID
- Hot
- Basaltic

TIMING
- Burial
- Short-lived
- Episodic

Workflow for diagenetic modeling

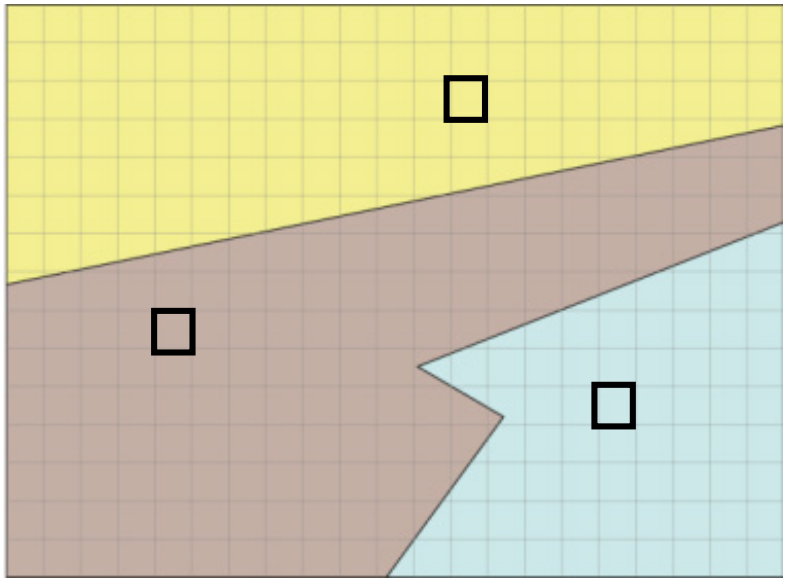


Workflow: 0D simulations

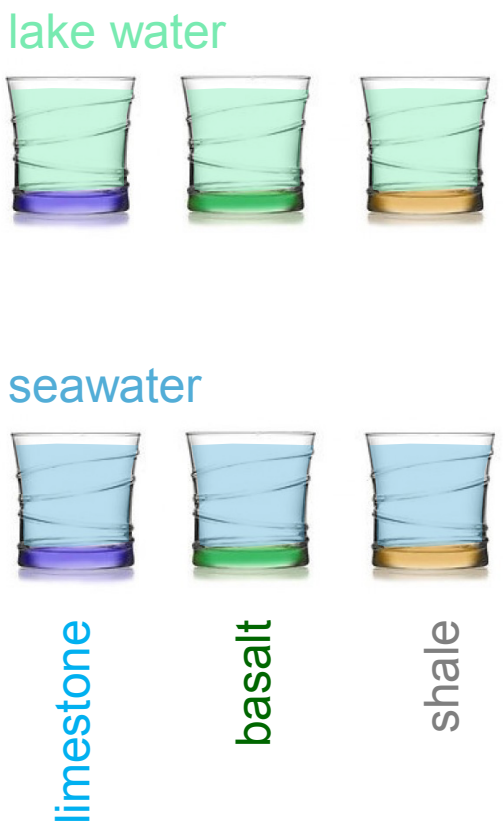
1. Silicifying fluid composition

2. Fundamental controls of carbonate replacement by silica

3. Spatial distribution of silicification



- single cell
- steady state
- vary lithology & fluids



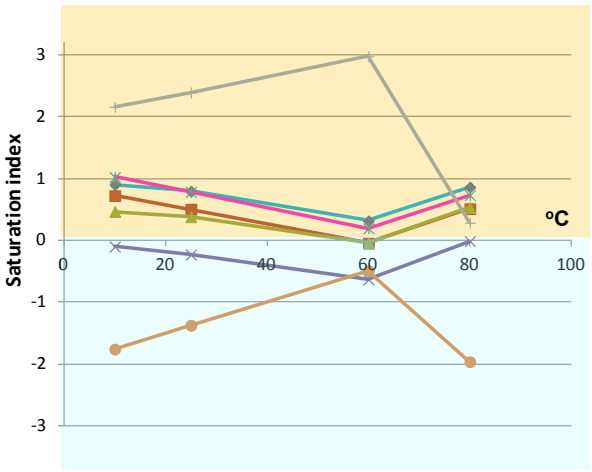
Results: 0D simulations

1. Silicifying fluid composition

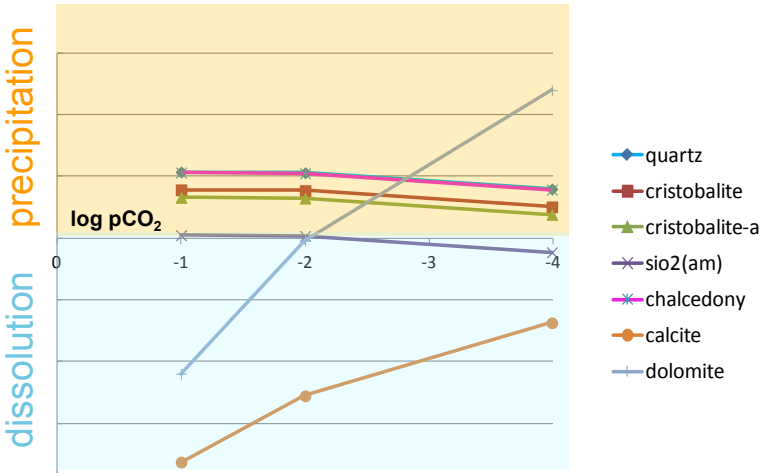
2. Fundamental controls of carbonate replacement by silica

3. Spatial distribution of silicification

sensitivity to temperature



sensitivity to CO_2



	Basalt 1	Basalt 2	Basalt 3	Granite	Shale
Aptian seawater	o	x		x	x
Lake water	x	oo	x	x	o
Deionized water	o	o	x	x	x
Groundwater 1	o	o		x	
Groundwater 2		o			

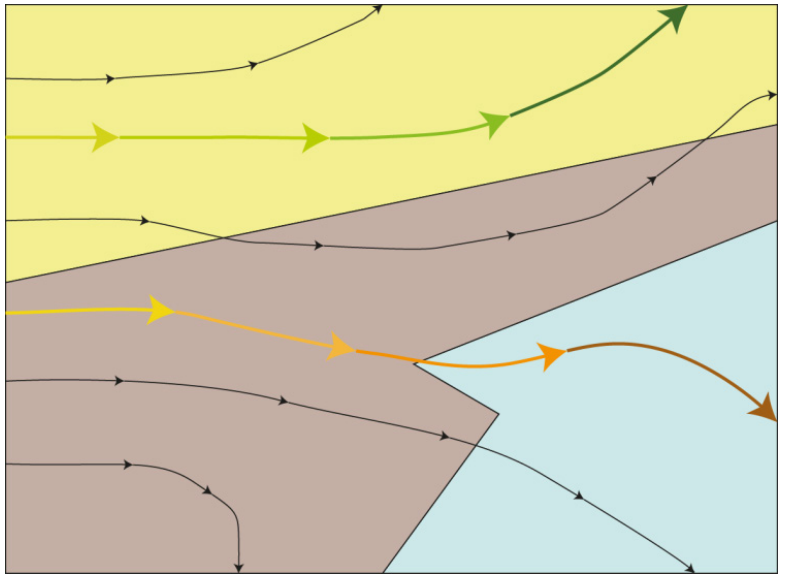
success at producing a silicifying fluid	
o	success at 25C
o	success at high pCO2
x	failed

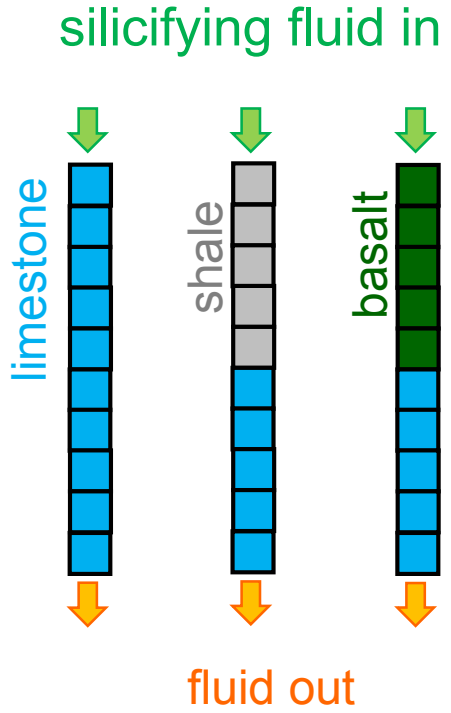
Workflow: 1D simulations

2. Fundamental controls of carbonate replacement by silica

1. Silicifying fluid composition

3. Spatial distribution of silicification





evaluate:

- Fluids
- Lithologies

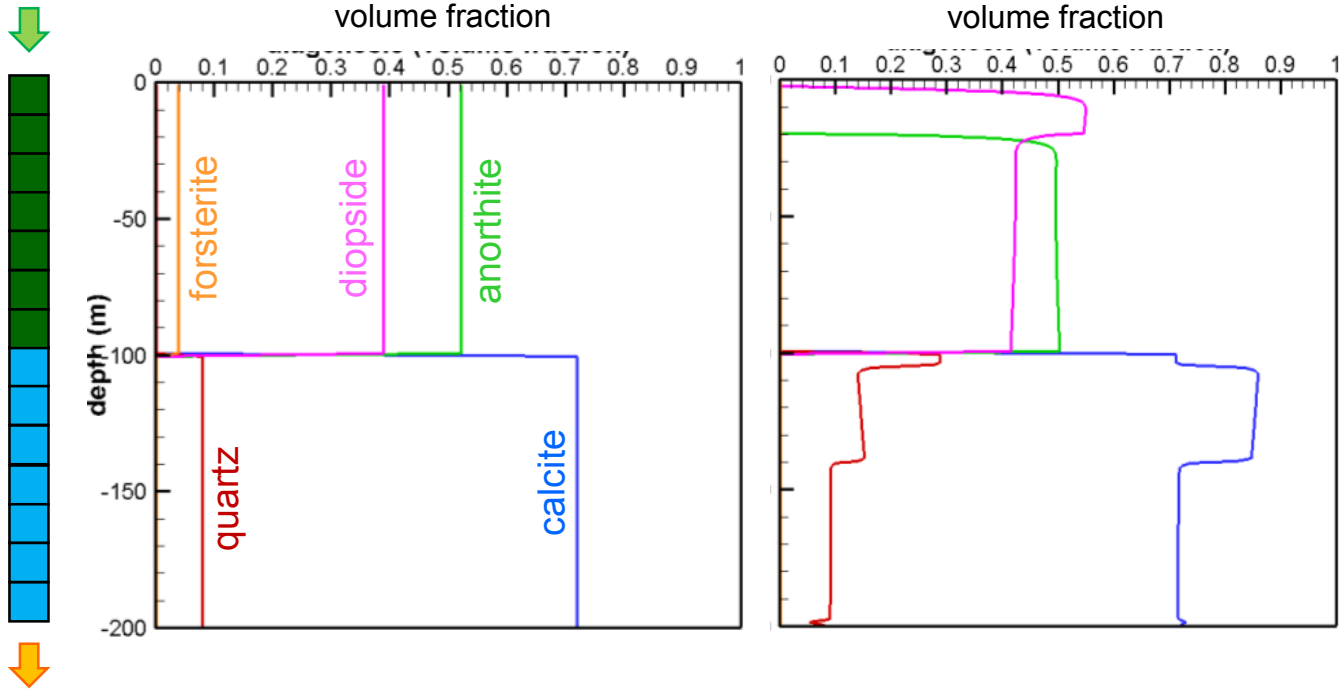
- Flow rate
- pCO2
- Temperature
- Time

Results: 1D simulations

1. Silicifying fluid composition

2. Fundamental controls of carbonate replacement by silica

3. Spatial distribution of silicification

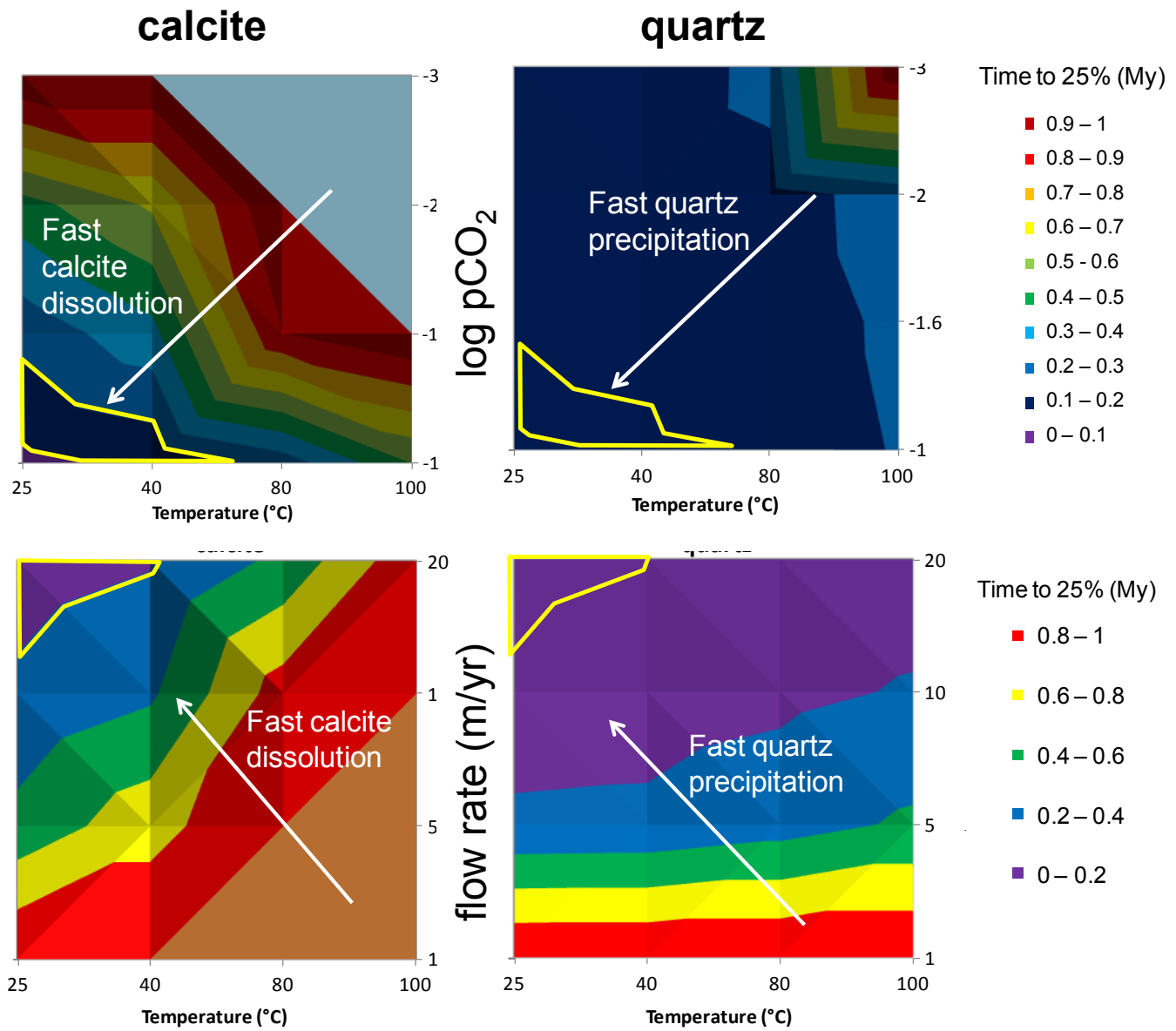


Results: 1D simulations

1. Silicifying fluid composition

2. Fundamental controls of carbonate replacement by silica

3. Spatial distribution of silicification



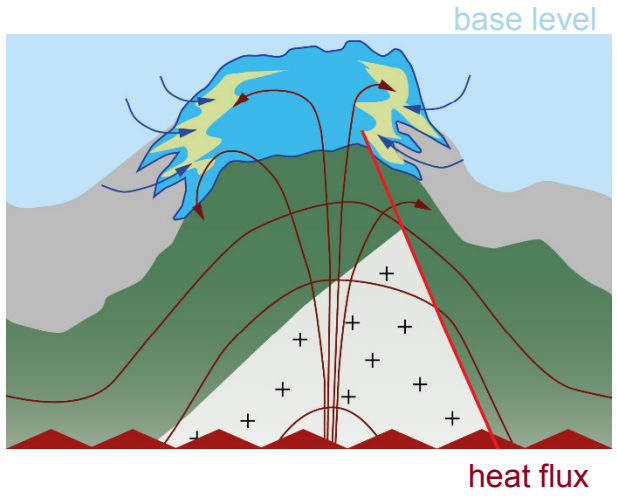
Workflow: 2D conceptual models

1. Silicifying fluid composition

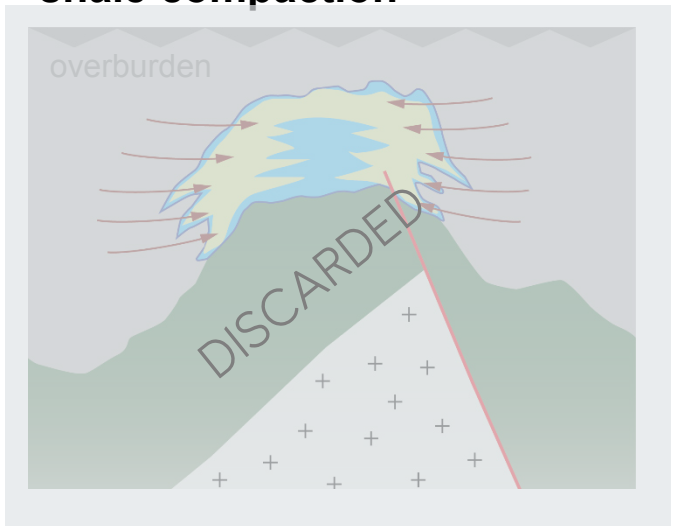
2. Fundamental controls of carbonate replacement by silica

3. Spatial distribution of silicification

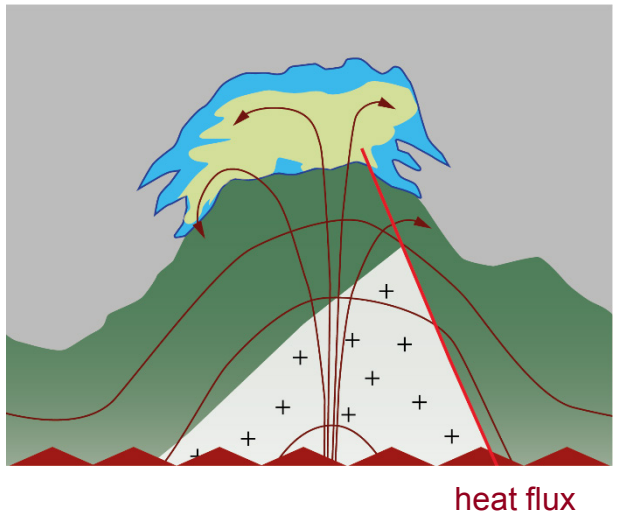
kohout circulation



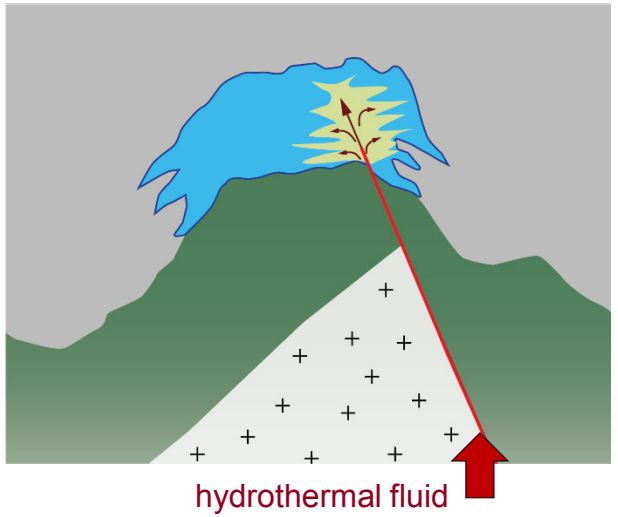
shale compaction



geothermal convection



hydrothermal flow through faults



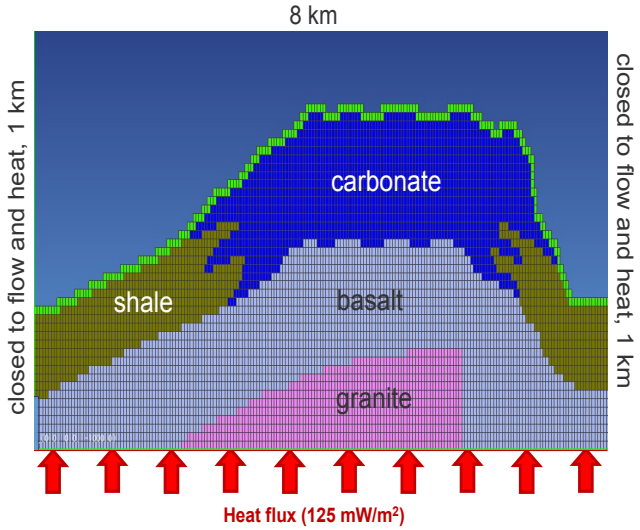
Workflow: 2D simulations

1. Silicifying fluid composition

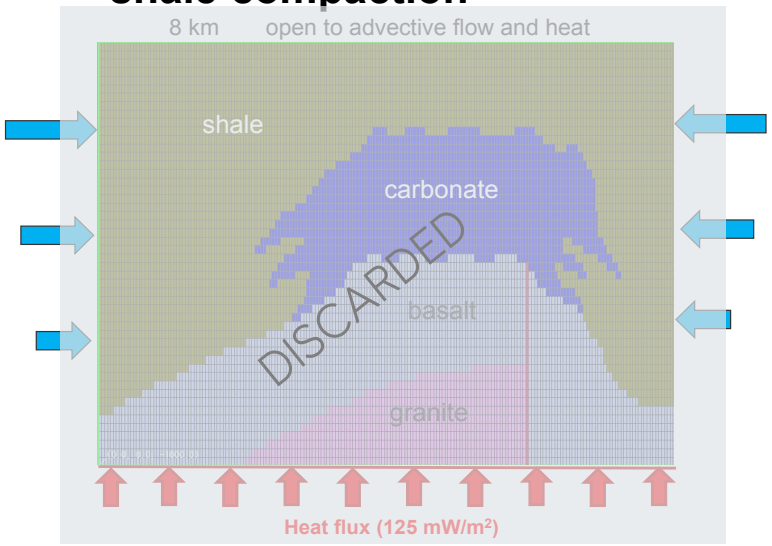
2. Fundamental controls of carbonate replacement by silica

3. Spatial distribution of silicification

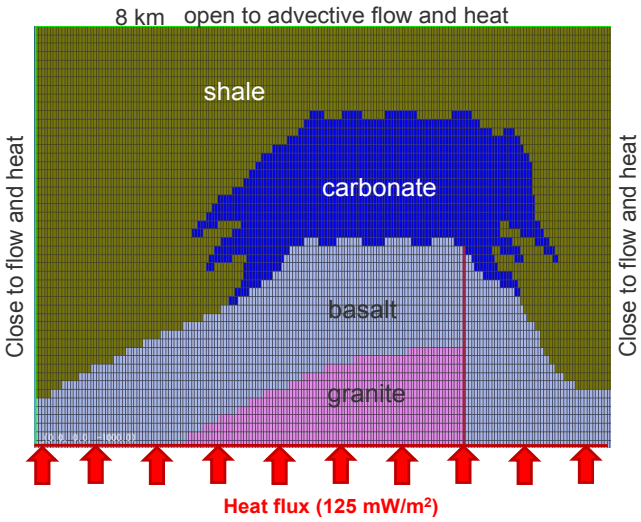
kohout circulation



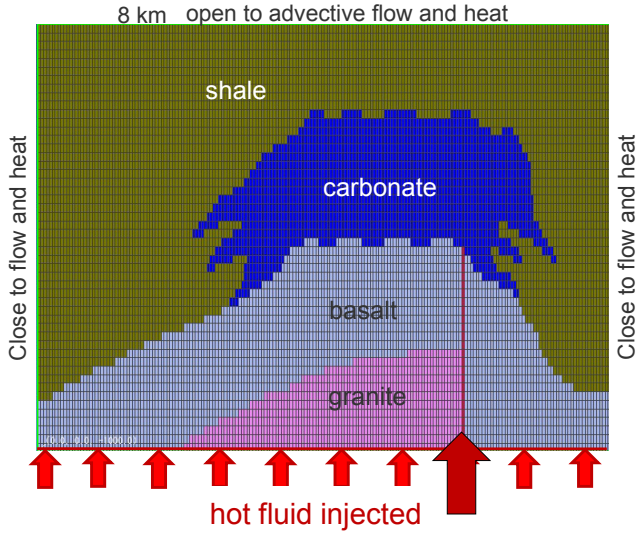
shale compaction



geothermal convection



hydrothermal flow through faults



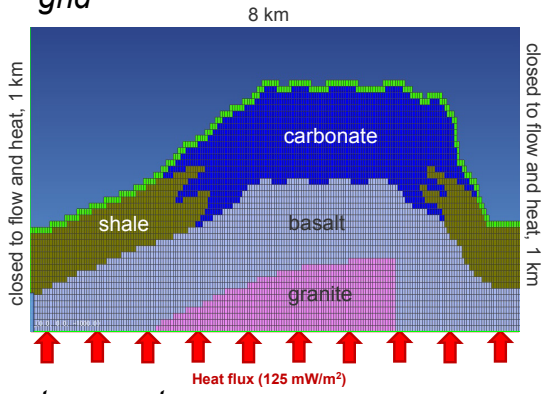
Results: 2D Kohout circulation, 1 Ma

1. Silicifying fluid composition

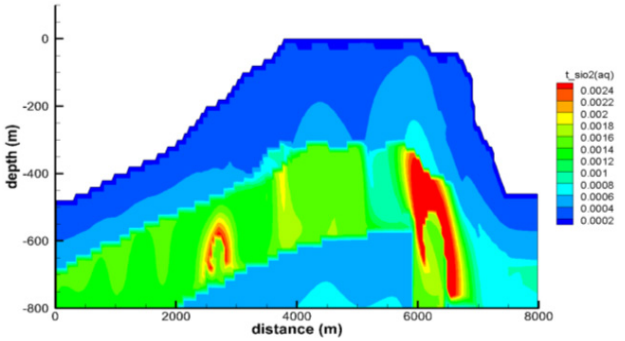
2. Fundamental controls of carbonate replacement by silica

3. Spatial distribution of silicification

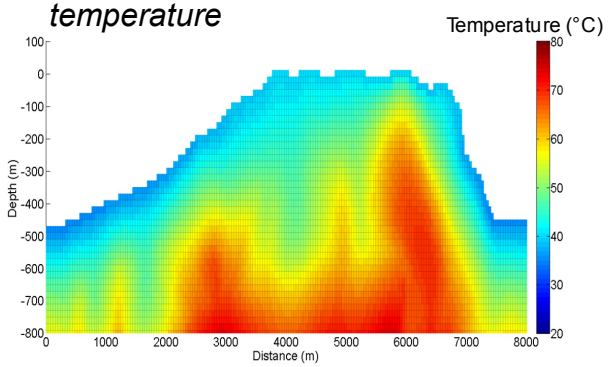
grid



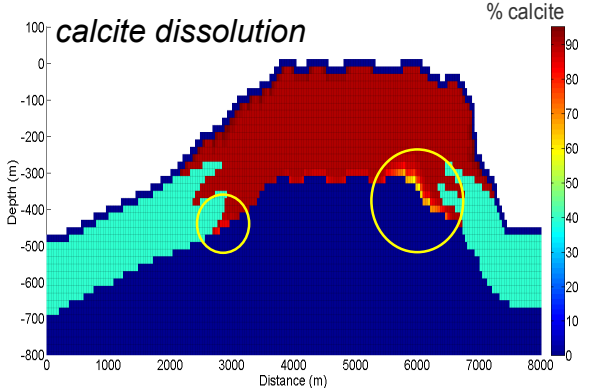
silica concentration in fluid (0,5 Ma)



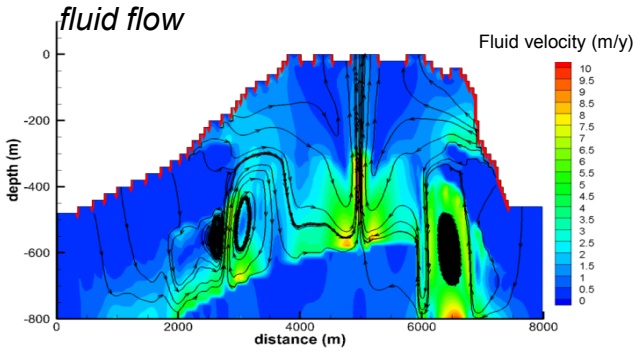
temperature



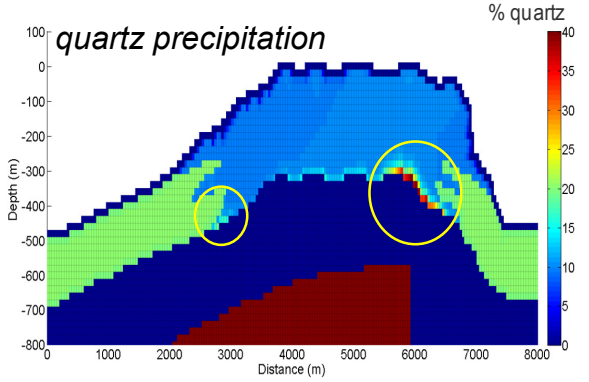
calcite dissolution



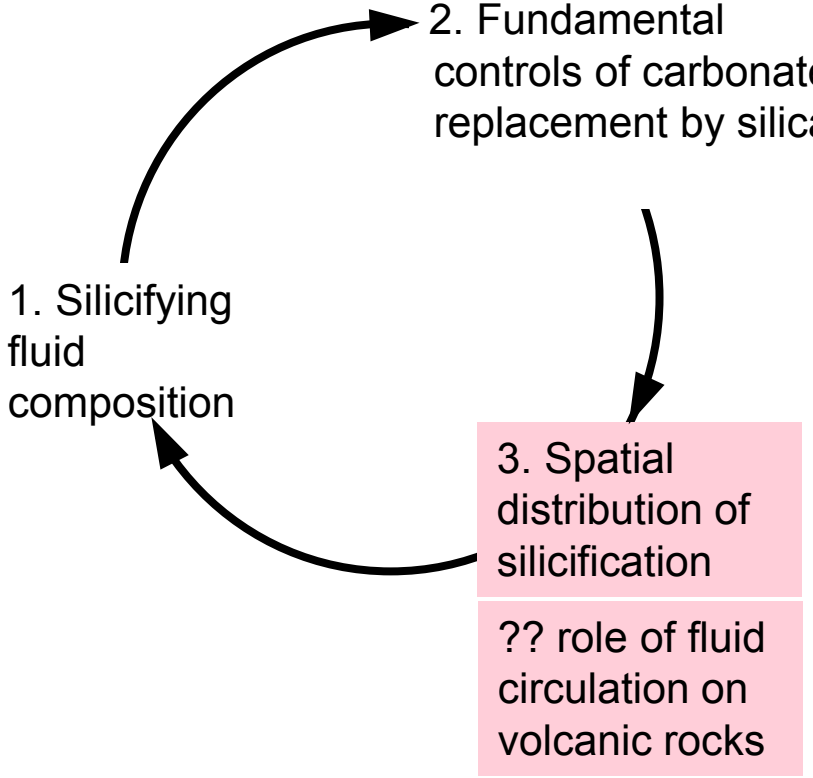
fluid flow



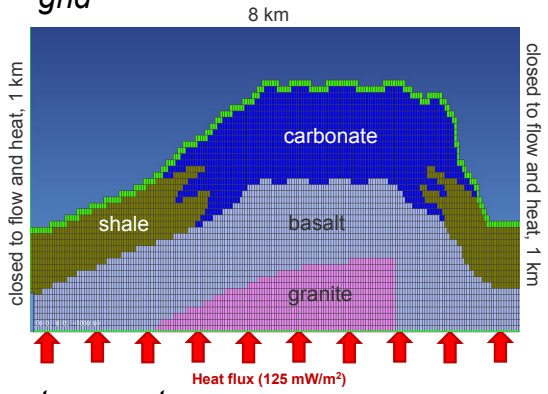
quartz precipitation



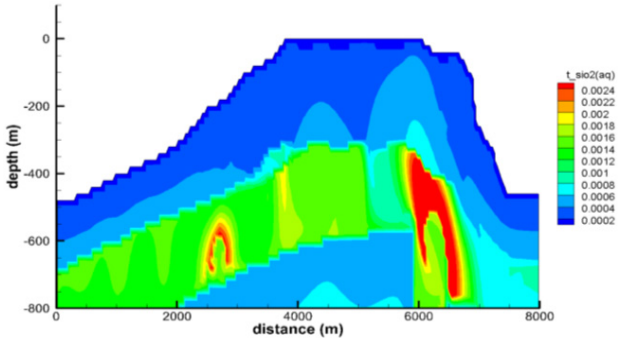
Workflow: iterations



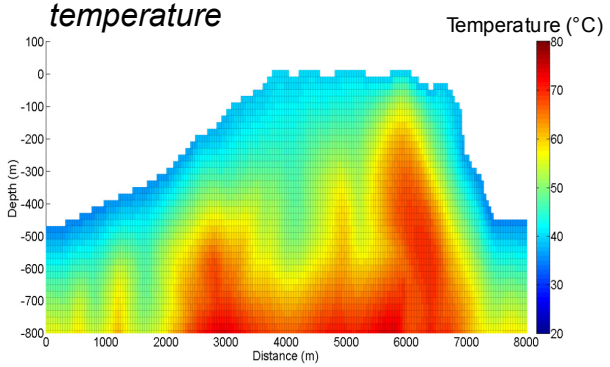
grid



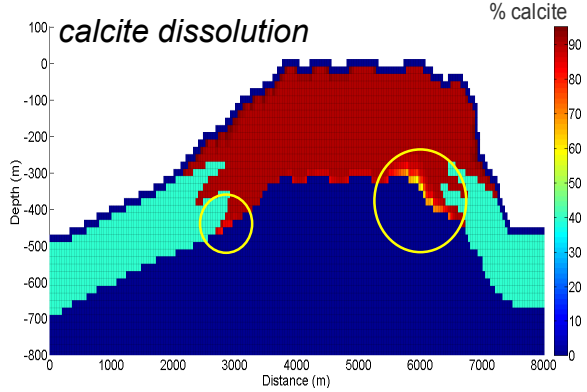
silica concentration in fluid (0,5 Ma)



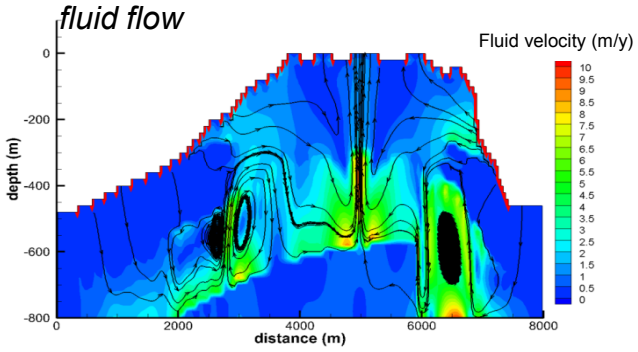
temperature



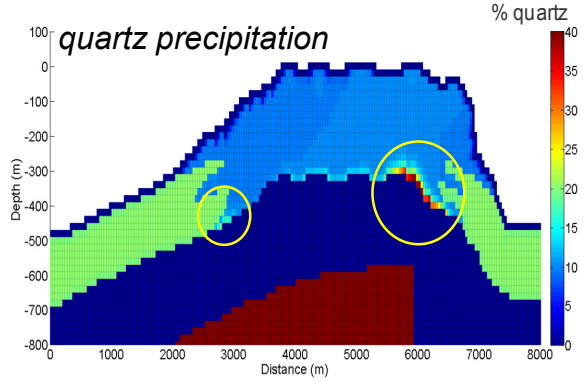
calcite dissolution



fluid flow



quartz precipitation



Conclusions

- Massive and pervasive replacement of carbonate by silica **is difficult**: common parameter space for simultaneous calcite dissolution and silica precipitation is narrow
- Requires very specific geologic setting and conditions:
  - An effective driver for fluid flow, such as an elevated geothermal gradient
  - An effective silica-rich fluid, for example hydrothermal fluids circulated through volcanic/igneous rocks
  - It is favored by rapid flow rates and high CO_2
  - Can be favored by cooling, for example by lake water intruding into the carbonate buildup
  - May require some initial silica in the system (biogenic? clay diagenesis? other?)

- This style and scale of alteration can probably only be found in similar geological settings and not elsewhere
- Reactive transport modeling is a valuable tool to evaluate diagenetic processes and reservoir quality trends