Integrated Experimental and Modeling Studies of Mineral Carbonation as a Mechanism for **Permanent Carbon Sequestration** in Mafic/Ultramafic Rocks

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Zhengrong Wang
Yale University

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS
August 20-22, 2013

Organizations

- Yale University: Jay Ague, David Bercovici, Edward Bolton, Shun-ichiro Karato, Michael Oristaglio, and Zhengrong Wang
- University of Hawaii: Kevin Johnson, Eric Hellebrand
- University of Maryland: Wen-lu Zhu
- Collaborators:
  - PNNL: Pete McGrail and Herbert Schaef

Presentation Outline

- Project Overview
- Technical Status & Accomplishments
- Key Findings
- Summary
- Accomplishment and future directions
- Appendix

Benefit to the Program

- Program goal being addressed
  - Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ± 30 percent.
- Benefits statement
  - This research project is developing new methodology, integrating both geochemical and geomechanical experiments with reactive transport modeling, for making rigorous estimates of the permanent carbon sequestration potential in mafic and ultramafic rocks subjected to ***in situ*** **mineral carbonation**.

Project Overview:
Goals and Objectives

- Determine, through geochemical experiments, reaction rates of the key mineral carbonation reactions in the system,

  [mafic rocks + H_2O + CO_2] → [carbonate rocks + byproducts],

  by studying the influence of pressure, temperature, ionic activity, surface area, pH and extent of reaction.
- Determine, through geomechanical experiments, how pore space of basalts and other mafic/ultramafic rocks evolves during carbonation reactions, especially in the competition between cracking and pore constriction and collapse.
- Develop a calibrated numerical simulation model of *in situ* mineral carbonation that can be used to design field experiments by predicting how lab experiments scale up.

Project Overview:
Success Criteria

Geochemical experiments	Experimental results for reaction products and rates repeatable to ±10% with consistent P/T trends Simulation code reproduces reaction products and rates from subset of laboratory experiments with maximum error of ±10%, after adjusting input parameters. Code predicts reaction rates to ±20% outside range used to adjust parameters.
Geomechanical experiments	Permeability and fracture strength measurements repeatable in experiments with fluid-rock mixtures to ±20%. Simulation code reproduces reaction products and rates from subset of laboratory experiments with maximum error of ±20%, after adjusting input parameters. Code initially predicts reaction rates to ±30% outside range used to adjust parameters. With further refinements, code predicts reaction rates to within 20%. Scaling up simulations show convergence to within 20% with successive grid refinement and self-consistent trends.

Project Overview: Deliverables

- Database Table of thermodynamic parameters and kinetic reaction rates for the main mineral carbonation reactions of mafic/ultramafic rocks

- Codes for integrated geochemical/geomechanical modeling of mineral carbonation in 0D through 3D

- Plan for Site Assessment and Characterization for a large-scale field test in a “phase-II” project (expected field site is Big Island of Hawaii)

Technical Status

- Experimental setup
- Geochemical experiments and modeling
- Geo-mechanical experiments and modeling

Experimental setup

silicate rock **carbonate rock**

$$Mg_2SiO_4 + 2\,CO_2 \longrightarrow 2\,MgCO_3 + SiO_2$$

olivine **pyroxene**

$$2\,Mg_2SiO_4 + CaMgSi_2O_6 + 2\,CO_2 + 2\,H_2O \longrightarrow$$

$$CaCO_3 + MgCO_3 + Mg_2Si_2O_5(OH)_5$$

calcite **magnesite** **serpentine**

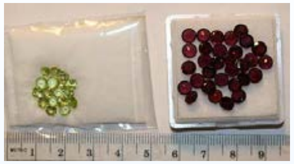
Mineral Carbonation

GEOCHEMICAL Experiments on Minerals

Understand the fundamental thermodynamics & kinetics

Cold seal and flow-through experiments on mineral powders to map reaction kinetics of mineral carbonation as a function of pressure, temperature, grain size, and other control variables

Model chemical reactions and mass transport



GEOMECHANICAL Experiments & Modeling

Understand the feedbacks: effects of chemical reactions on rock matrix and pore space

Flow and deformation experiments with monitoring of porosity and permeability changes during mineral carbonation reactions

Model rock deformation and evolution of pore space with damage theory
Understand mechanisms of stress fracturing

SCALE UP

INITIAL PORE SPACE

STRESS FRACTURES
PORE SPACE ALTERATION

REACTION KINETICS

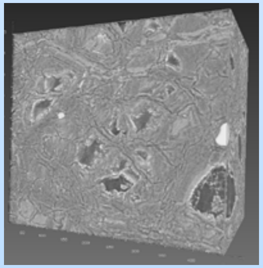
CHEMICAL
HYDROTHERMAL
& GEOMECHANICAL
PROCESSES

SCALE UP

Geochemical Experiments on Rocks

Understand rock assemblages in the lab

Cold seal and flow-through experiments on **rocks**



3D micro-tomogram *of carbonized dunite sample*

SCALE UP

Big Island, Hawai'i

MODELING & SIMULATION

Build an integrated simulation model for geochemical & geomechanical processes

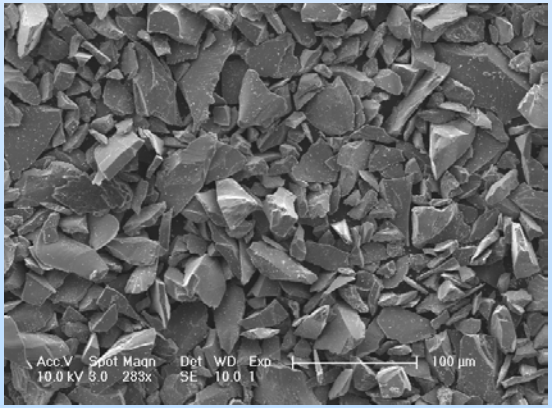
Scaling up simulations in 2D and 3D, calibrated by experiments and field work

DESIGN →

PHASE II FIELD STUDY

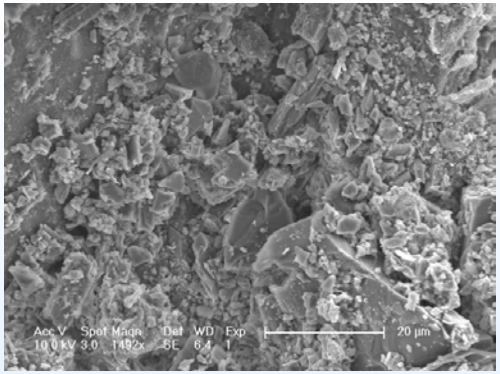
Geochemical experiments

YALE UNIVERSITY
GEOLOGY AND GEOPHYSICS

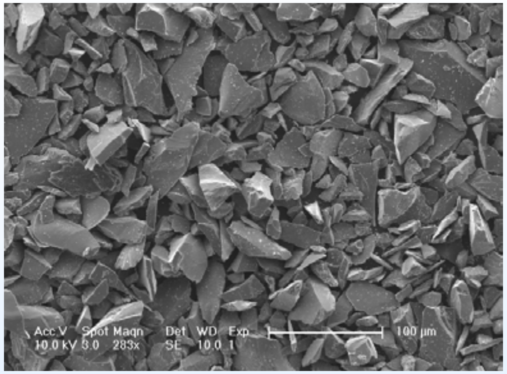


Samples

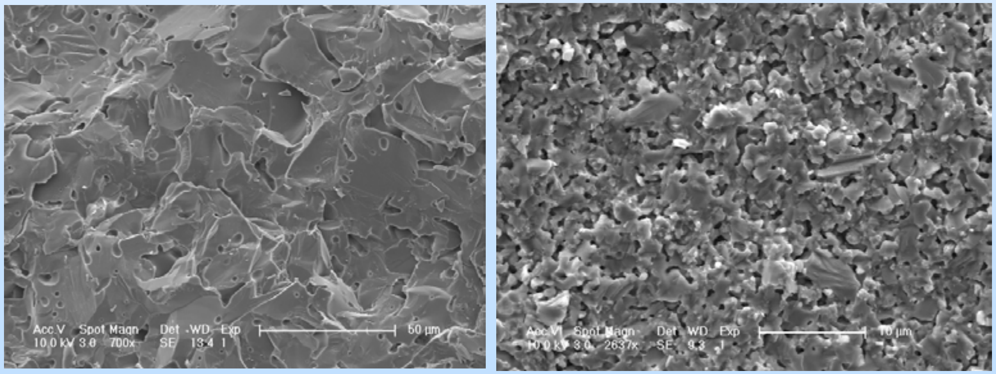
Gem-quality single crystals
(left: Olivine, Right: Garnet)



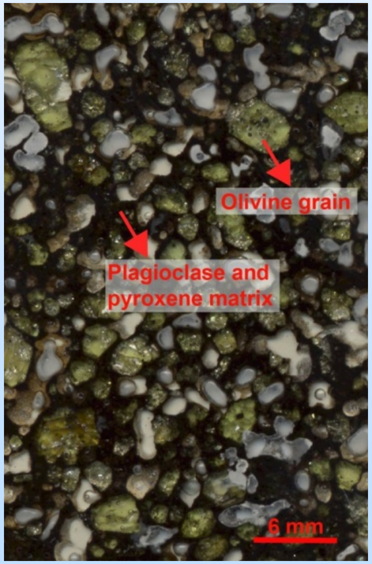
Basalt powder



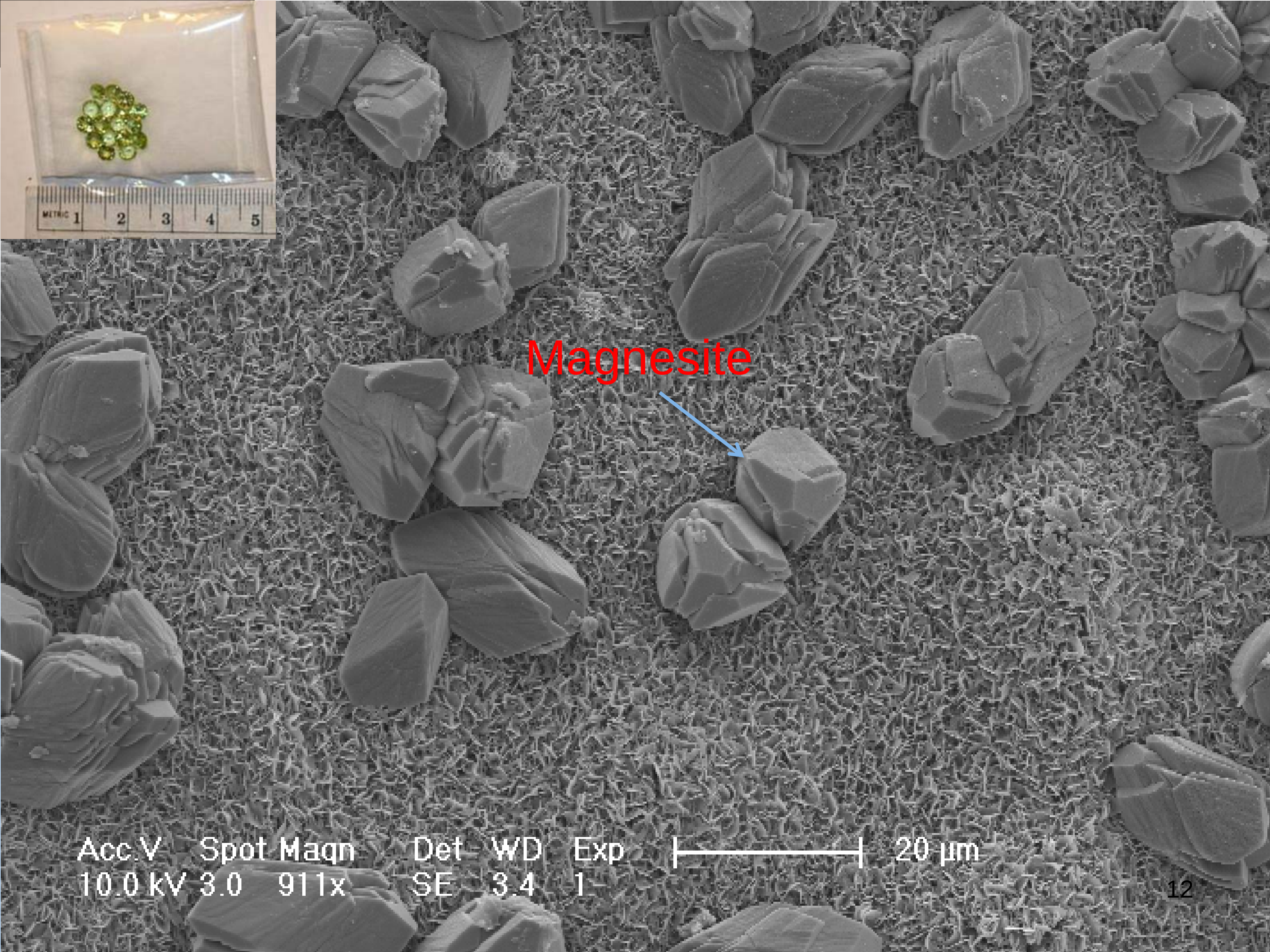
Olivine powder



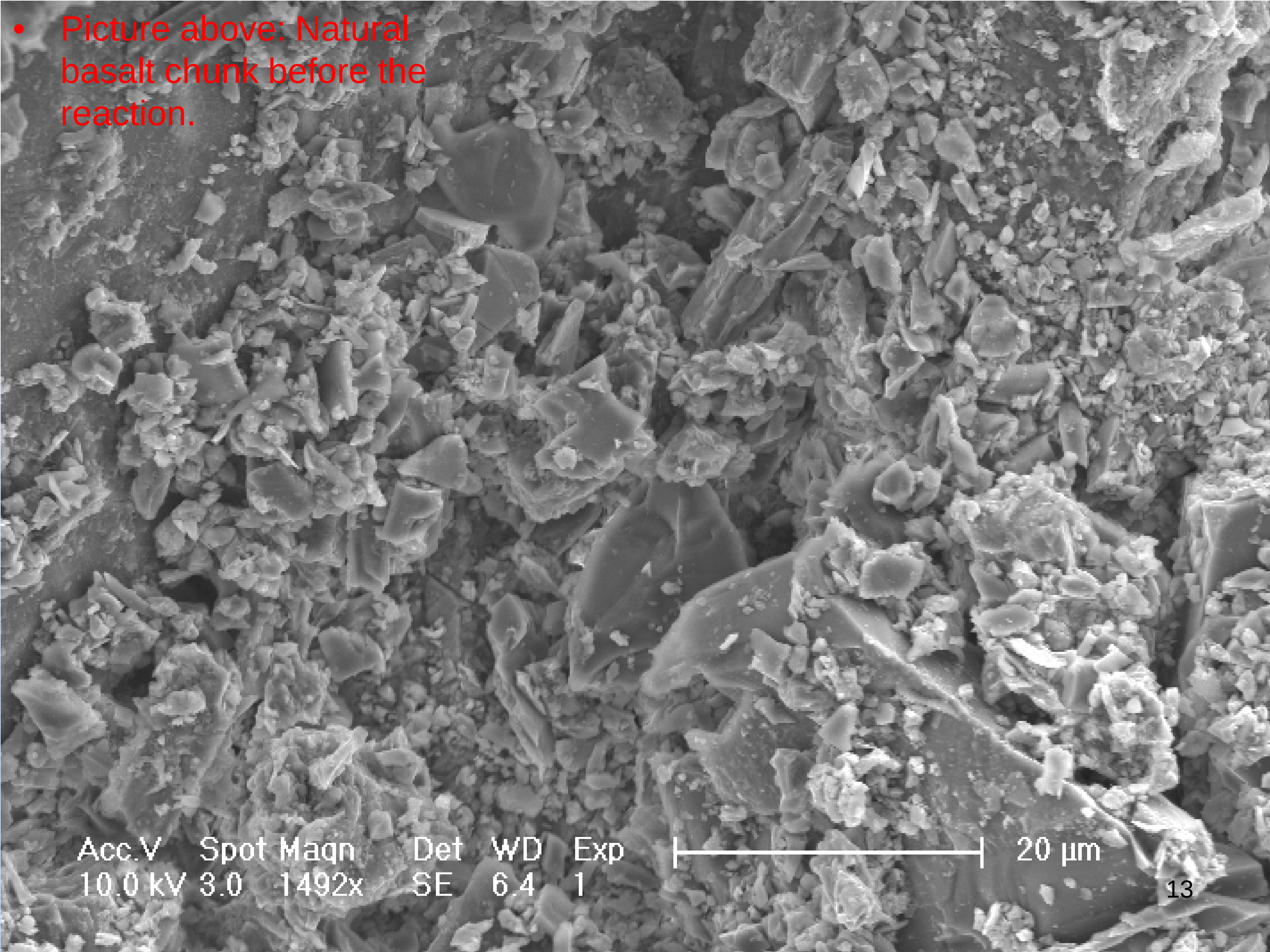
Sintered olivine and basalts

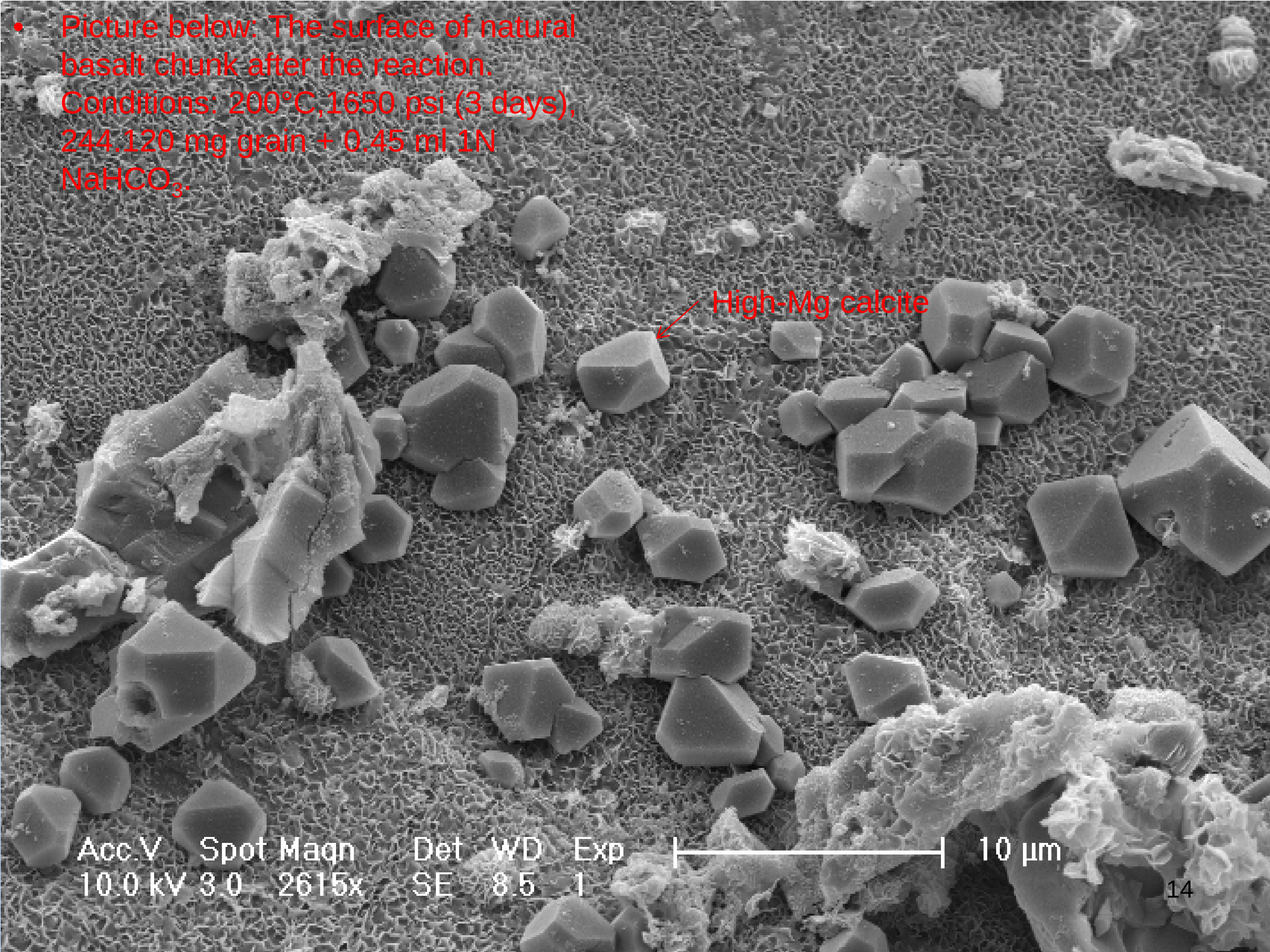


Picrite cube


METRIC 1 2 3 4 5
Magnesite
Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 911x SE 3.4 1
20 µm

- Picture above: Natural basalt chunk before the reaction.

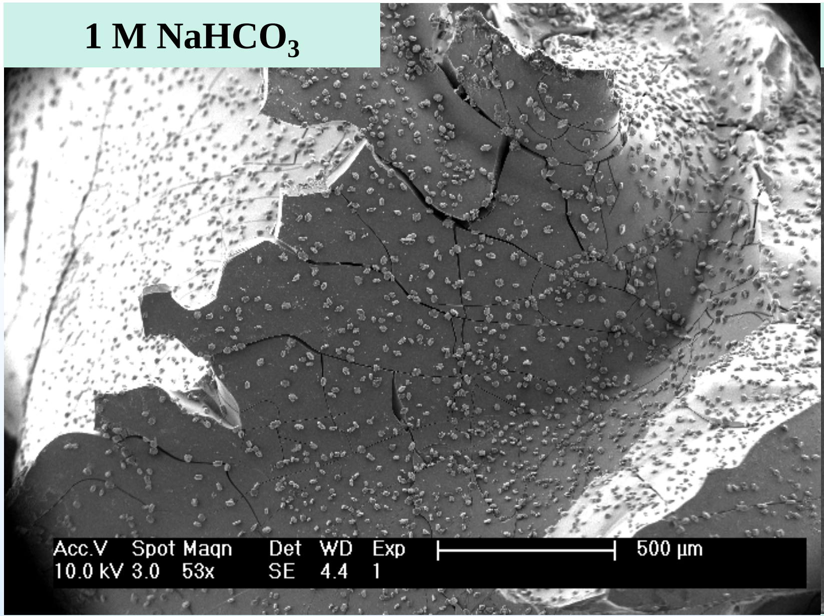




- Picture below: The surface of natural basalt chunk after the reaction. Conditions: 200°C,1650 psi (3 days), 244.120 mg grain + 0.45 ml 1N $NaHCO_3$.

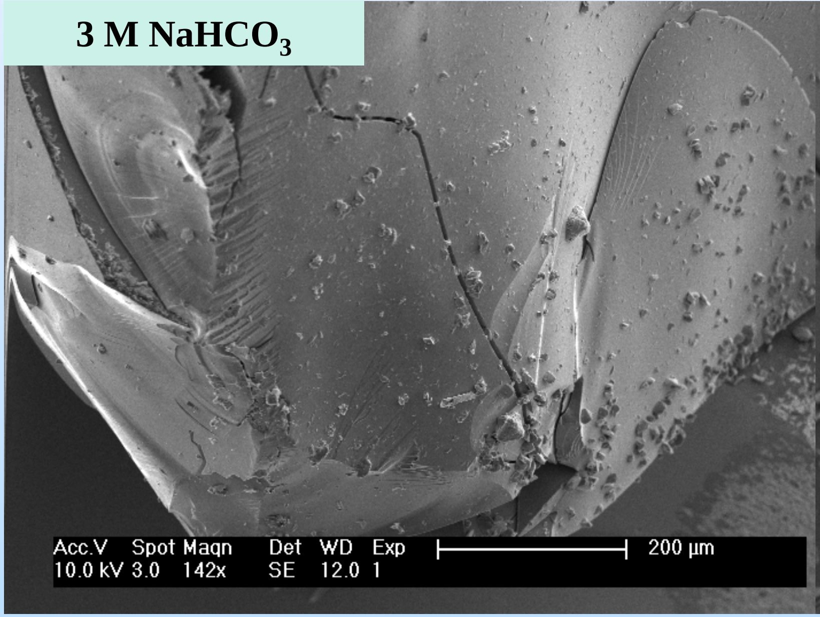
High-Mg calcite

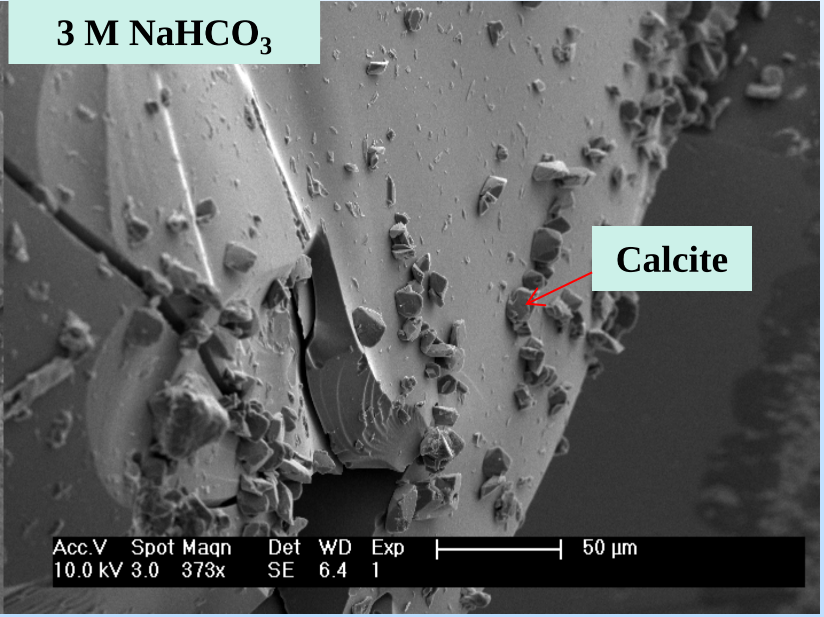
Basaltic glass piece (made by melting Connecticut basalt)


1 M $NaHCO_3$


1 M $NaHCO_3$

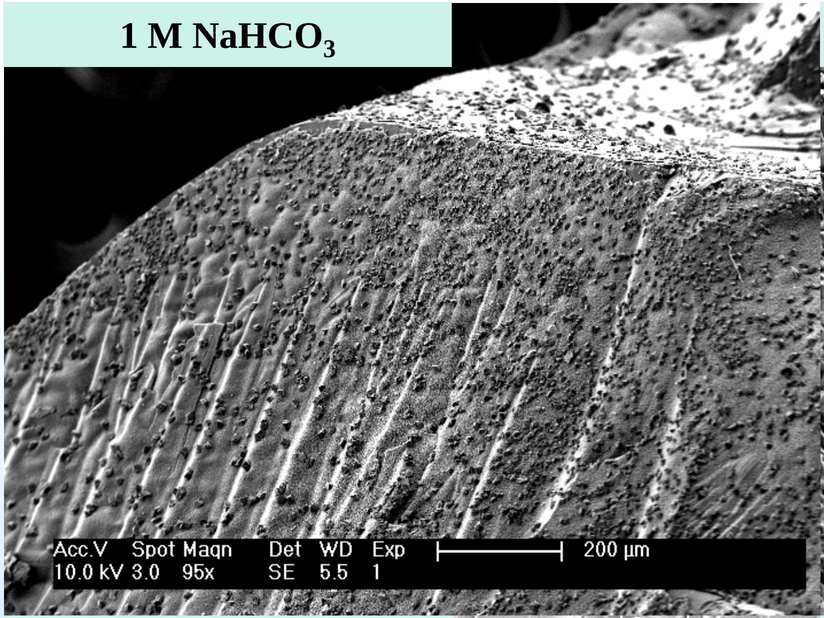
Calcite

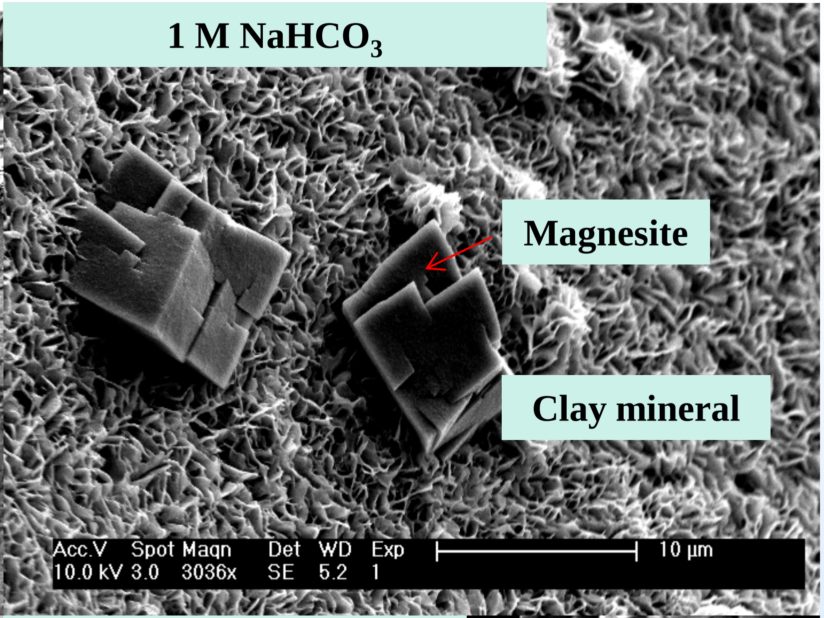

3 M $NaHCO_3$


3 M $NaHCO_3$

Calcite

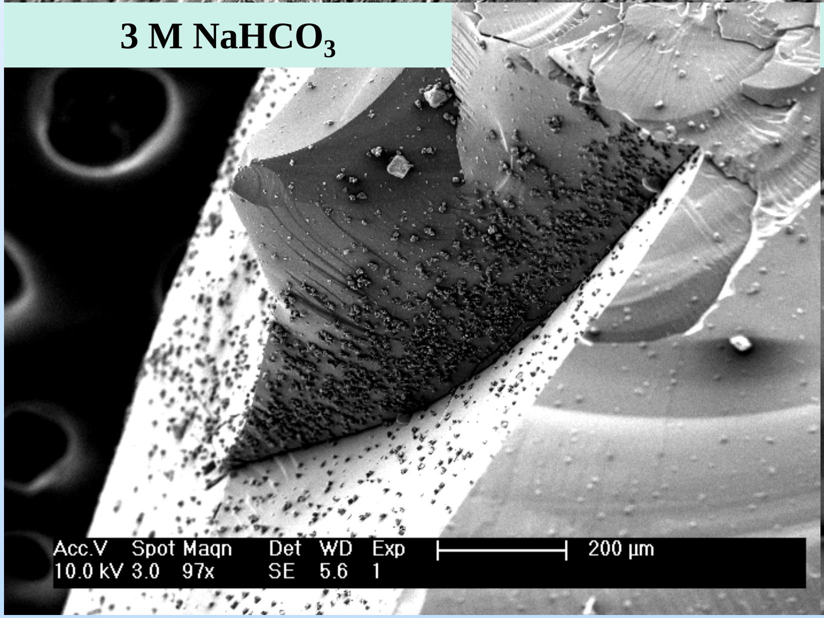
Basaltic glass (made by melting of Hawaiian picrite)

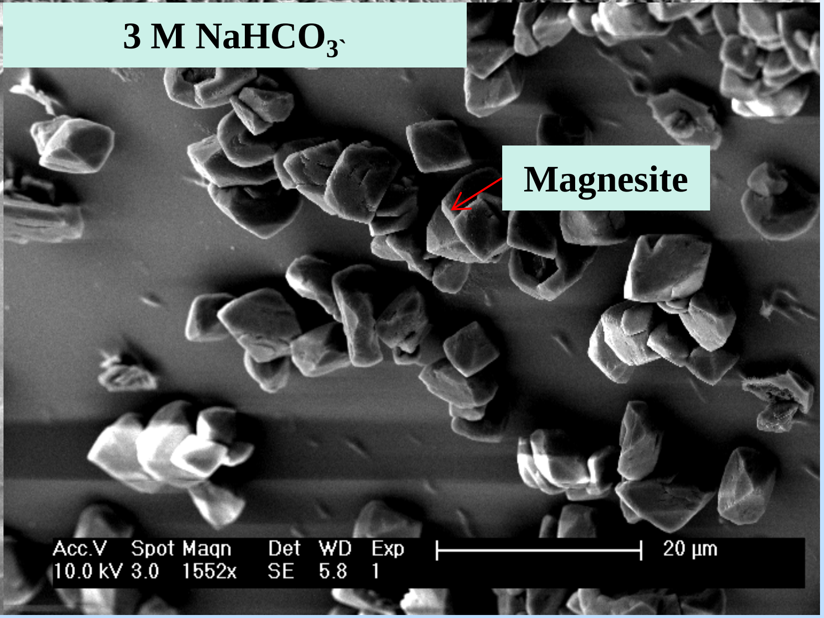

1 M NaHCO$_3$


1 M NaHCO$_3$

Magnesite

Clay mineral


3 M NaHCO$_3$


3 M NaHCO$_3$`

Magnesite

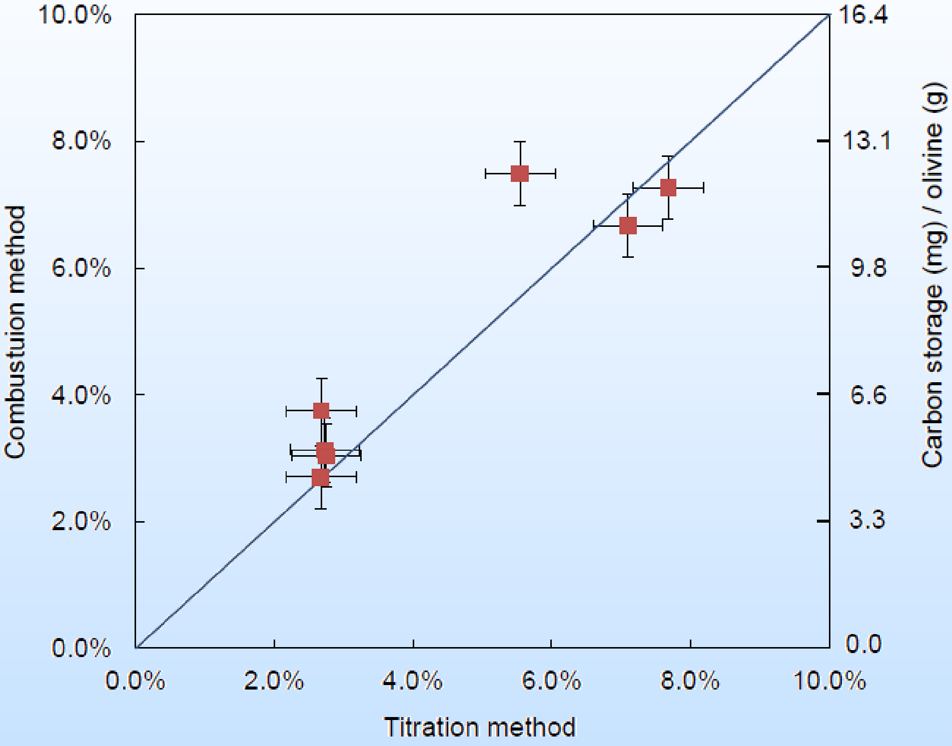
Carbonation fraction (CF)

$$Carbonation\,Fraction\,(CF) = \frac{\Delta DIC}{M_{olivine/basalt}} \times 100$$

$$Carbonation\ Fraction(CF) = \frac{\left(M_{Si} \times 2 - M_{Mg^{2+}}\right) \times W_{solution}}{M_{olivine/basalt}} \times 100$$

ΔDIC represents the moles of DIC consumed in an experiment as formation of carbonates (i.e., $MgCO_3$ and $FeCO_3$). $M_{olivine/basalt}$ are moles of divalent cations in the Olivine/basalt (including Fe^{2+}, Mg^{2+}, Ca^{2+}).

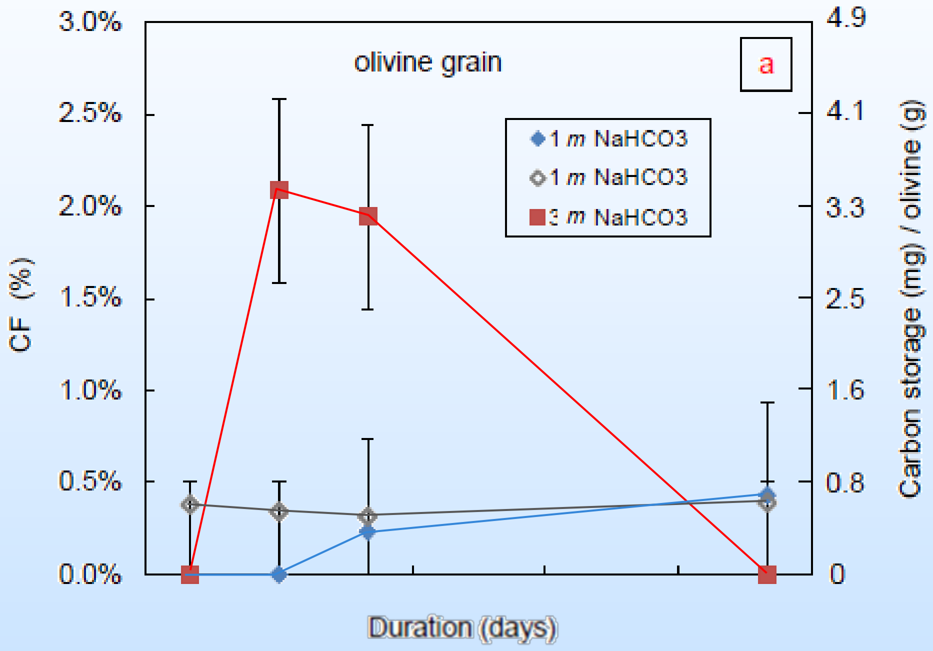
$$CS = CF \times \frac{12}{W_M} \times 2 \times 1000$$

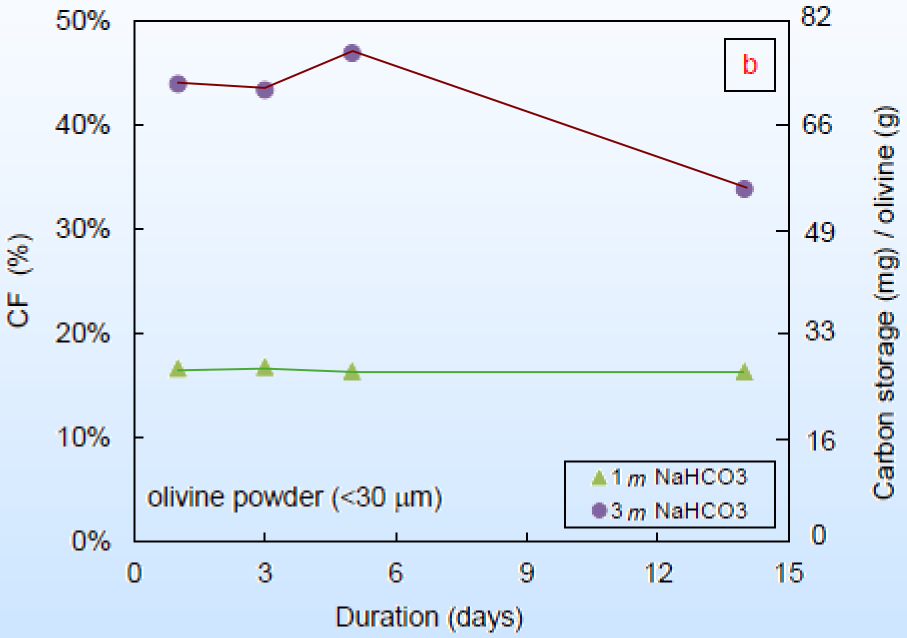


W_M is the molecular weight of olivine,
or average mass of the basalt that contains two moles of divalent cations

Qiu et al., 2013, submitted to Chemical Geology

Carbonation fraction (CF)



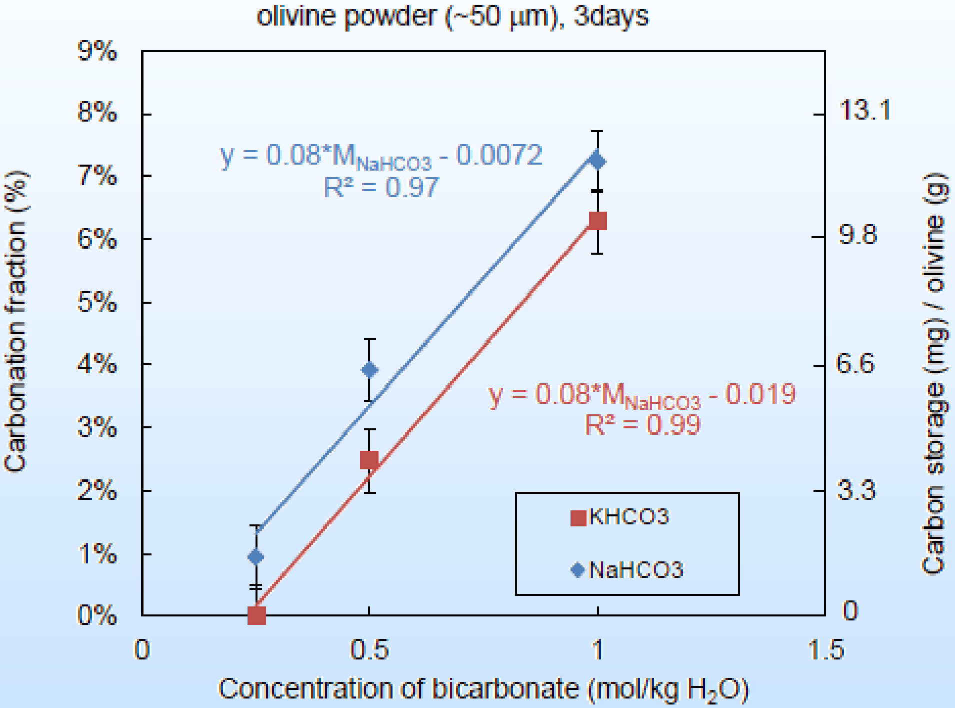


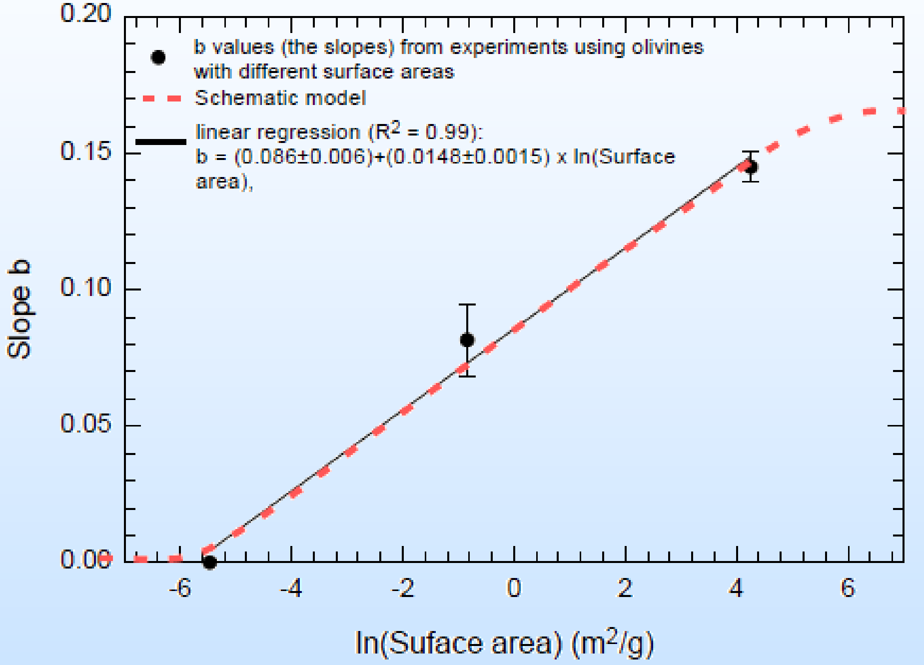
Questions:

1. Carbonation fraction increase with the concentration of $NaHCO_3$
2. Carbonation fraction rate is highest in the first couple of days, reach a plateau and then decrease with time
3. Carbonation fraction increase with decreasing grain size

Qiu et al., 2013, submitted to Chemical Geology

Effect of concentration of $NaHCO_3$ on Maximum carbonation fraction





$$CF_{\max} = [(0.086 \pm 0.006) + (0.0148 \pm 0.0015) \times \ln(S)] \times m_{DIC} + a$$

Qiu et al., 2013, submitted to Chemical Geology

Formation of secondary Mg-bearing silicate minerals

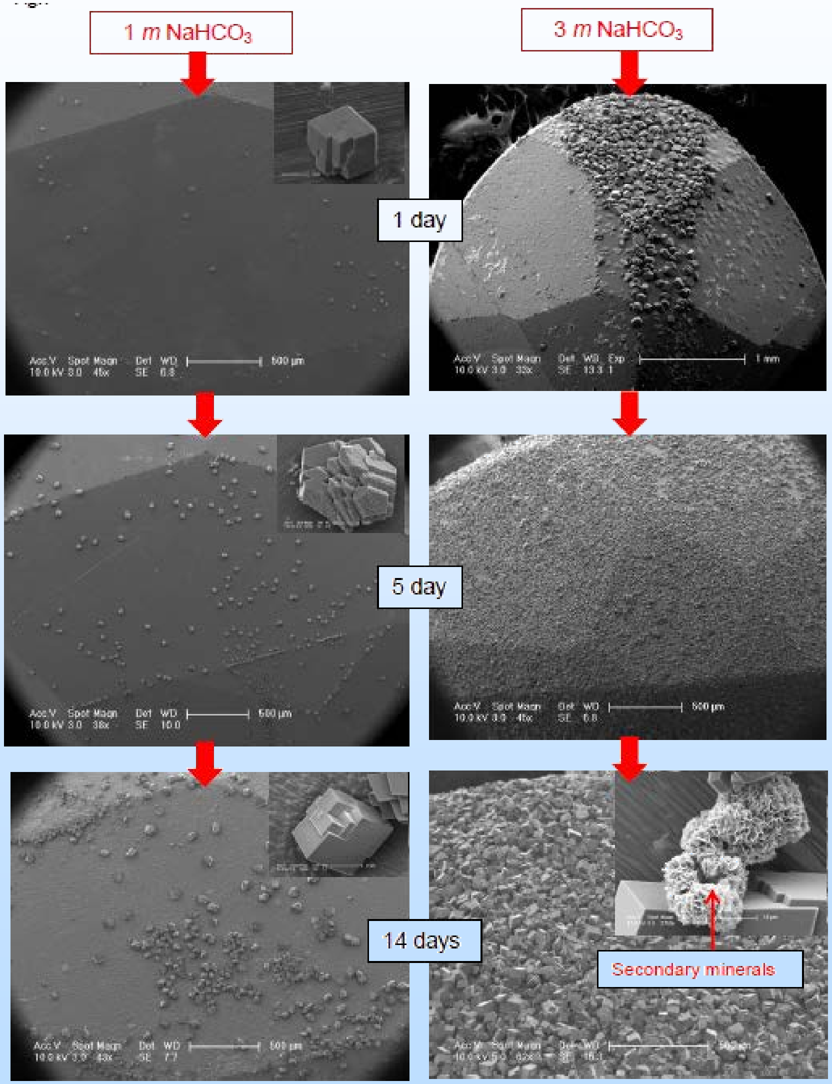
$$(Mg_{0.905}Fe_{0.095})_2SiO_4 + 4H^+ = 1.81Mg^{2+} + 0.19Fe^{2+} + H_4SiO_4\ (aq)$$

$$(Mg_{0.91}Fe_{0.09})_2SiO_4 + 4H^+ = 1.82Mg^{2+} + 0.18Fe^{2+} + H_4SiO_4\ (aq)$$

$$Mg^{2+} + CO_3^{2-} = Mg_2CO_3$$

$$3MgCO_3 + 4H_4SiO_4(aq) = Mg_3Si_4O_{10}\left(OH\right)_2 (Talc) + 3CO_2 + 7H_2O$$

$$3MgCO_3 + 2H_4SiO_4(aq) = Mg_3Si_2O_5\left(OH\right)_4 (\text{Chrysotile}) + 3CO_2 + 2H_2O$$



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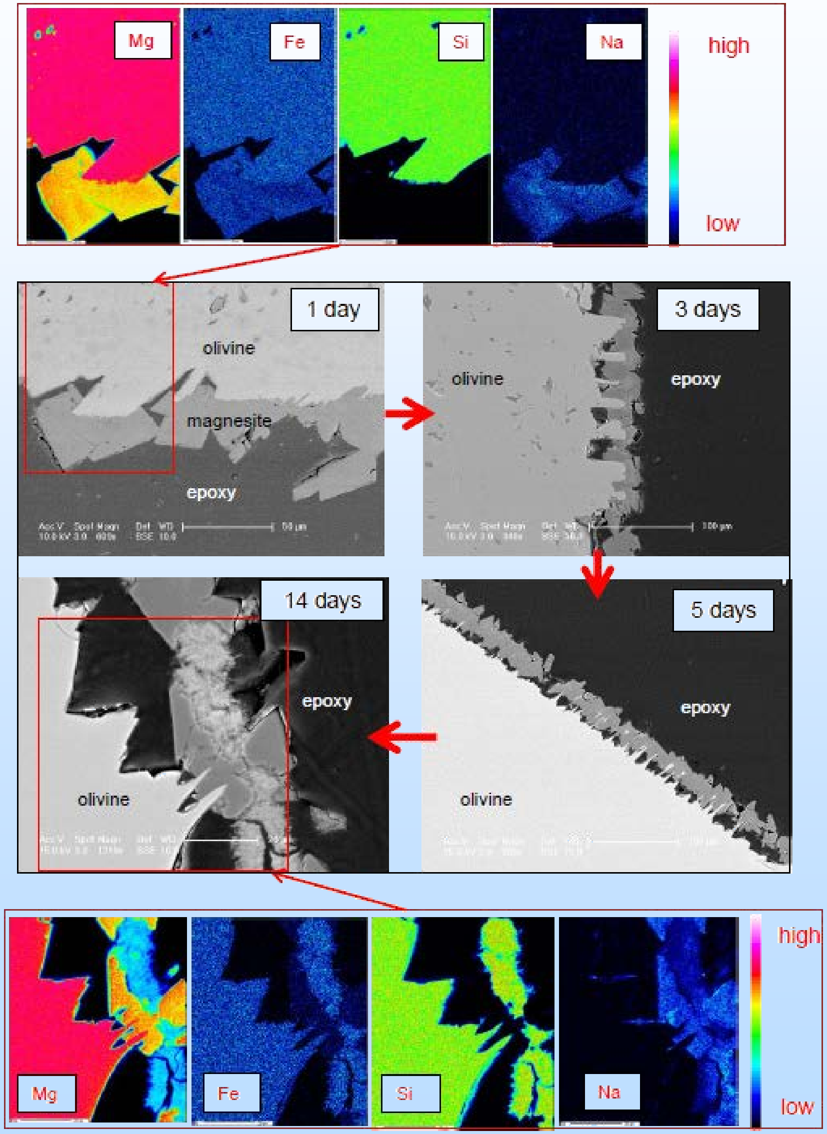

Qiu et al., 2013, submitted to Chemical Geology

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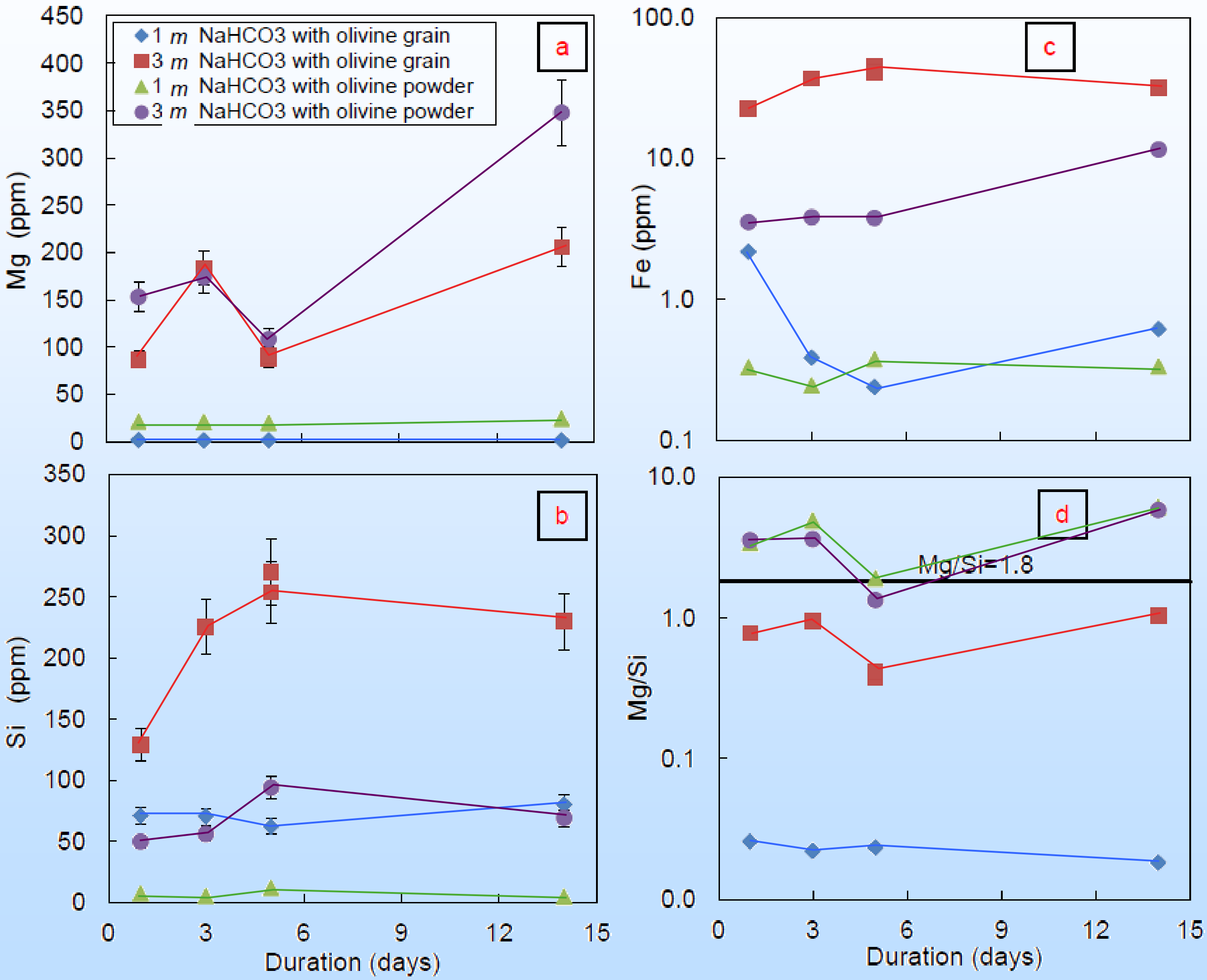
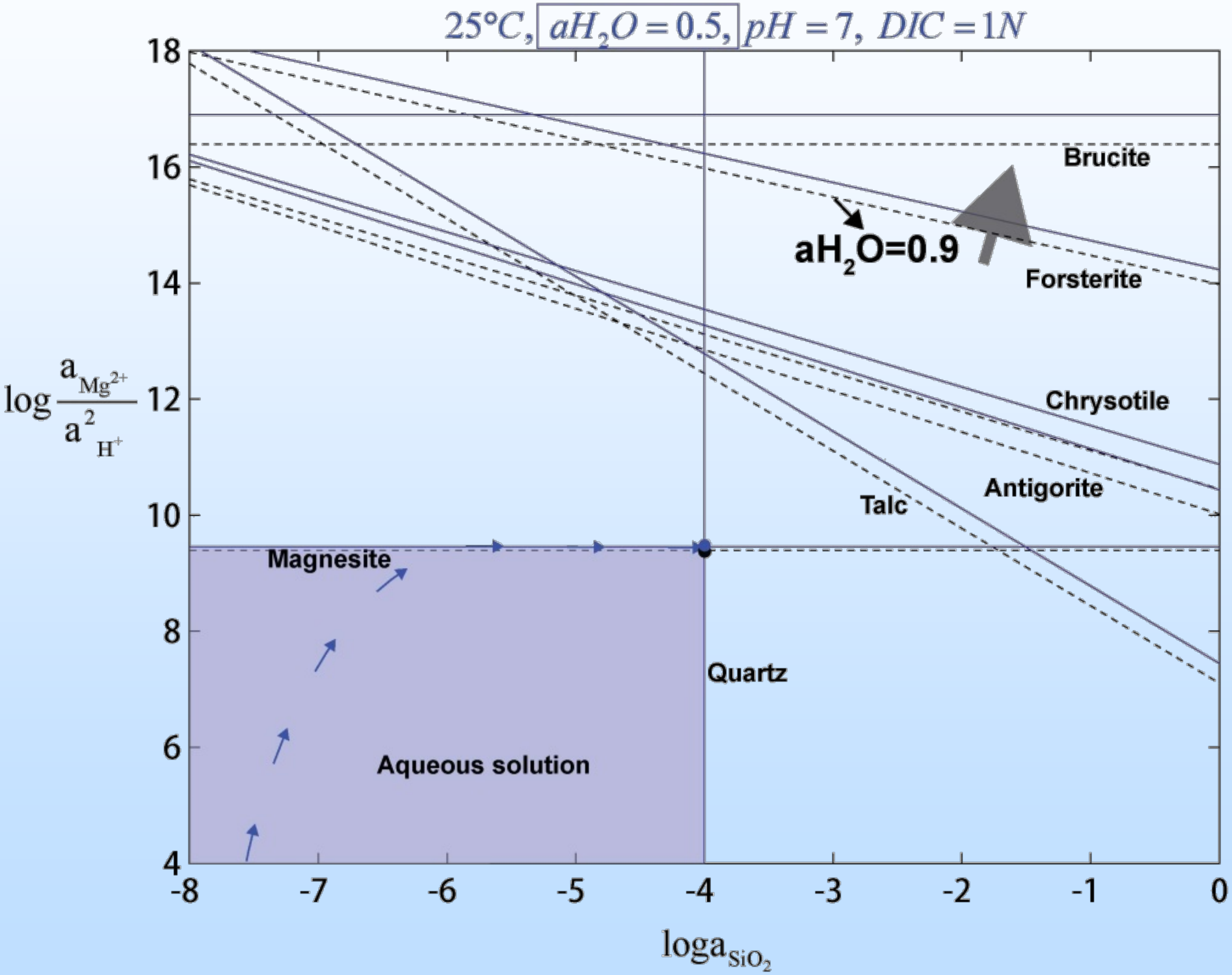


Qiu et al., 2013, submitted to Chemical Geology

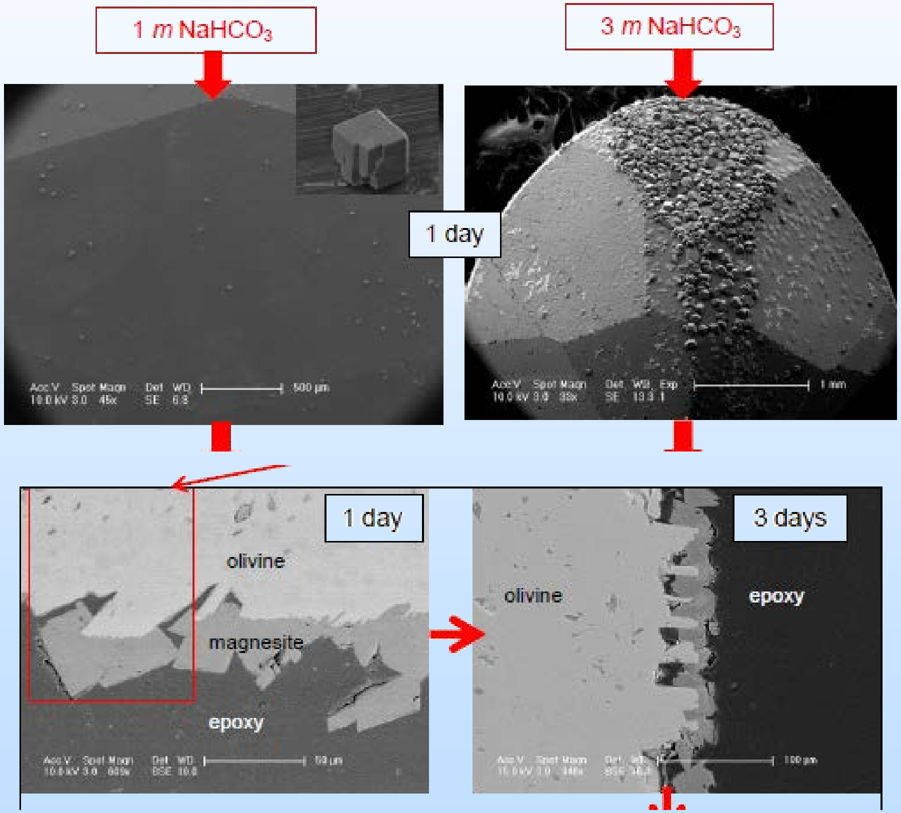
Thermodynamic consideration

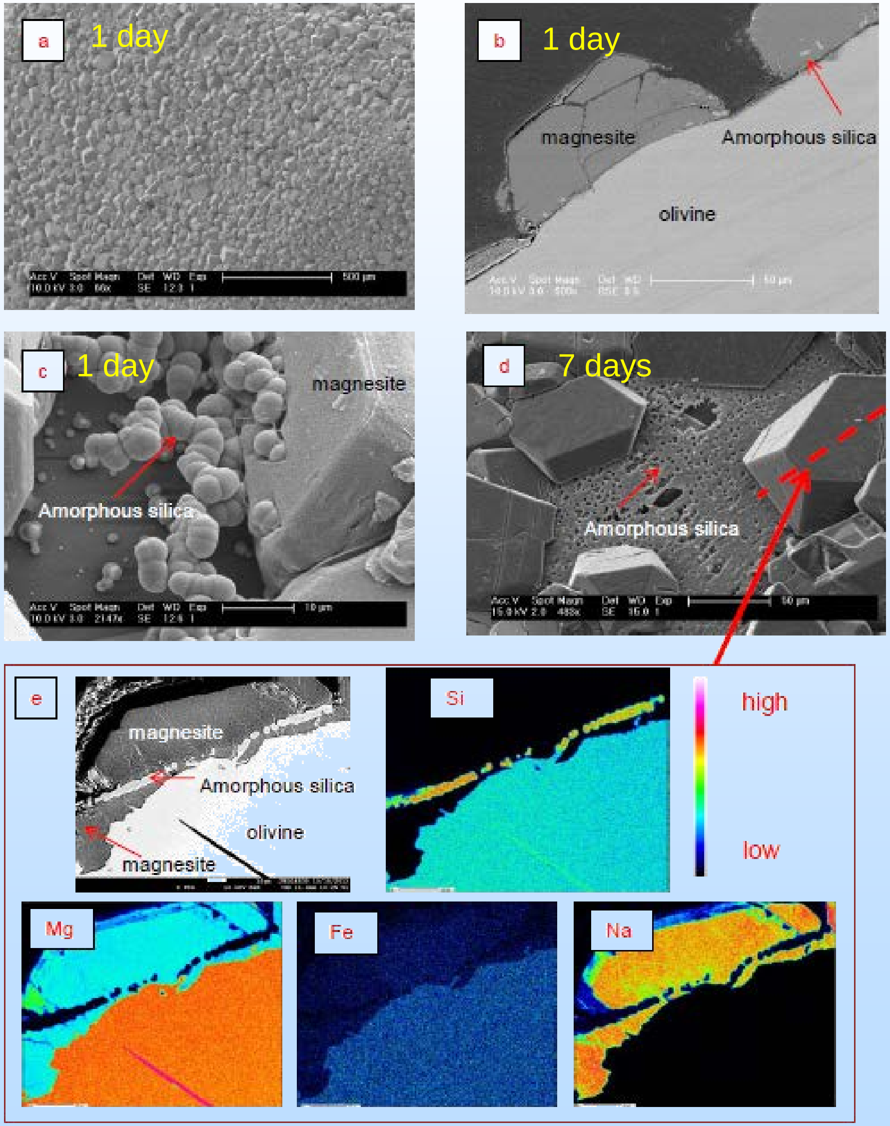


Qiu et al., 2013, submitted to Chemical Geology

Experiments with different water/rock ratio

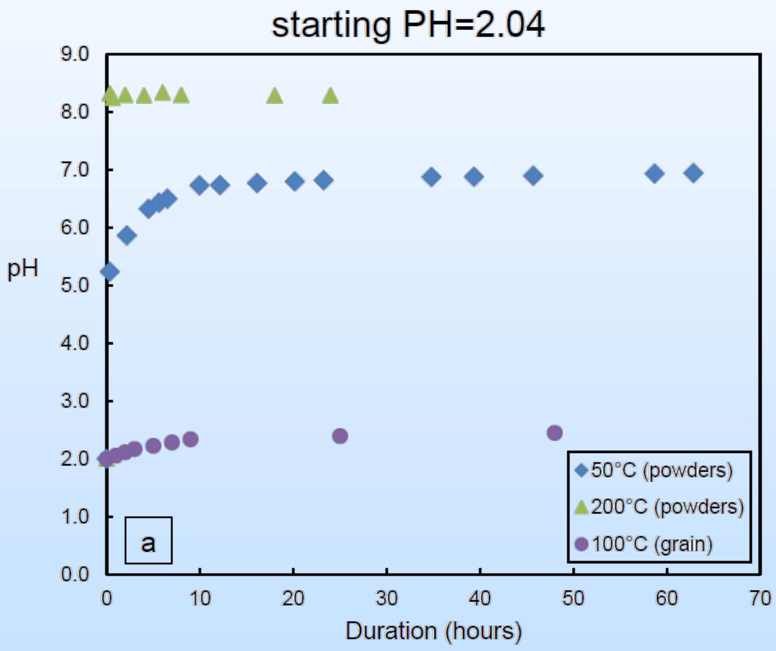
$$H_4SiO_4\ (aq) = SiO_2 \downarrow + 2H_2O$$

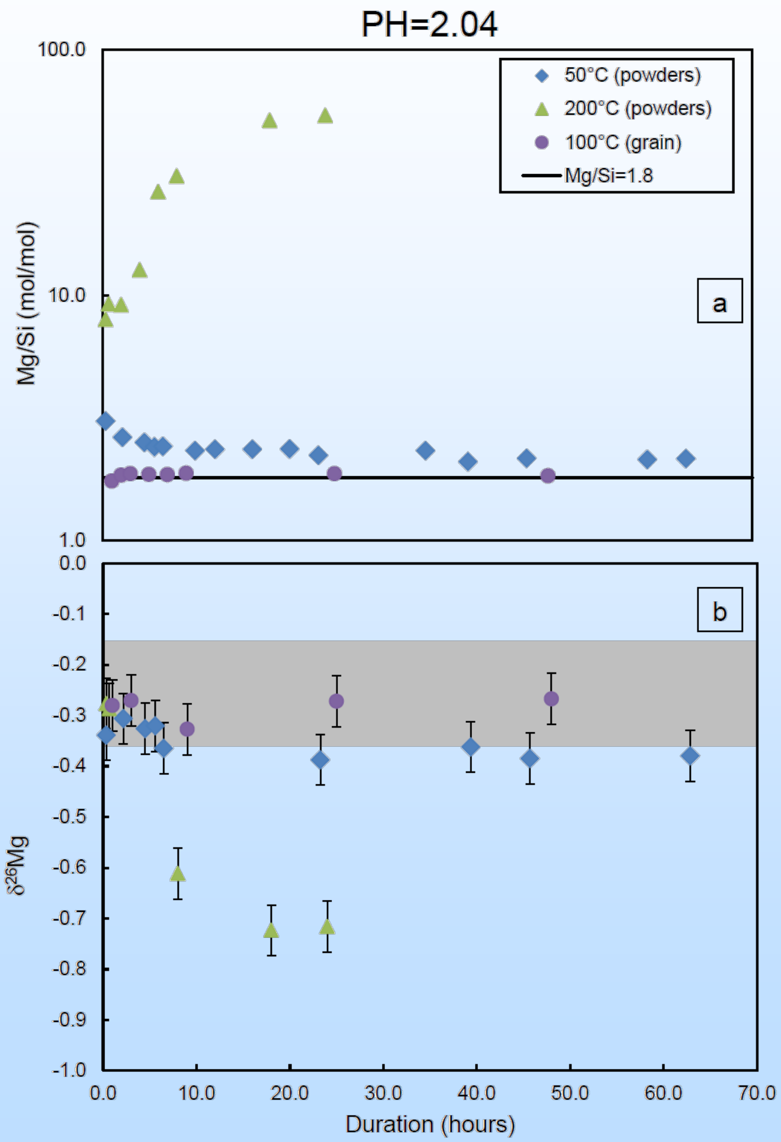




Qiu et al., 2013, submitted to Chemical Geology

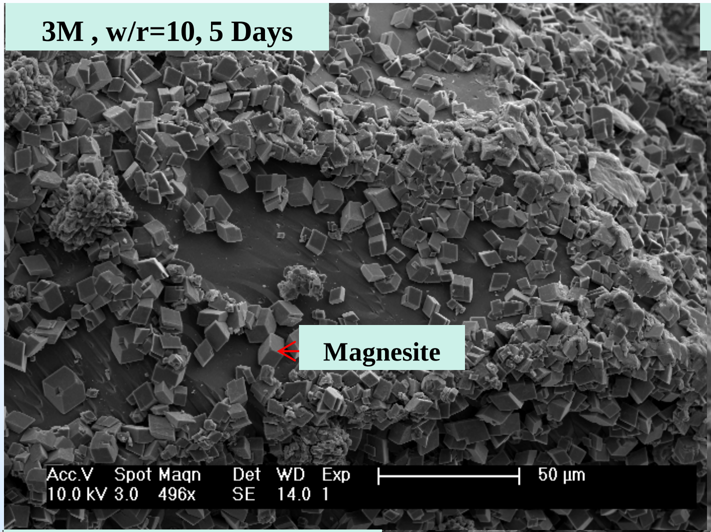
Mg isotope fractionation during dissolution

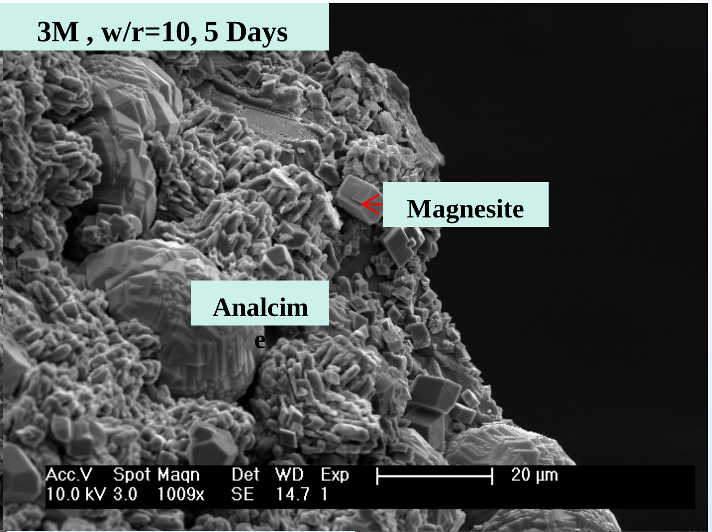


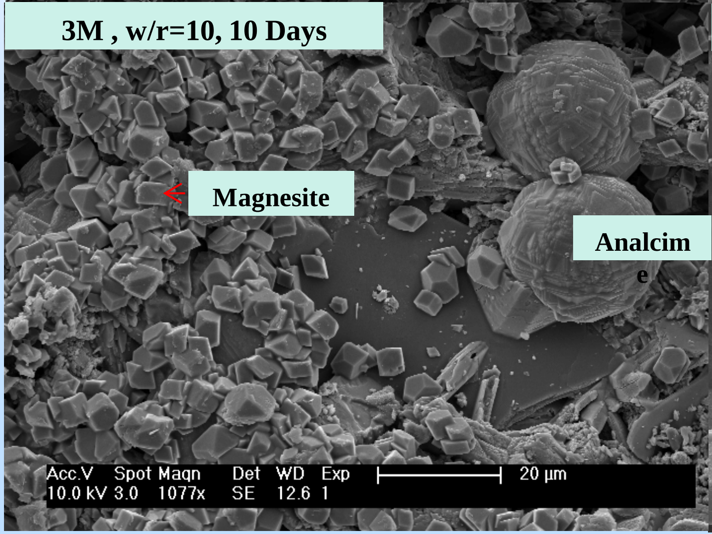


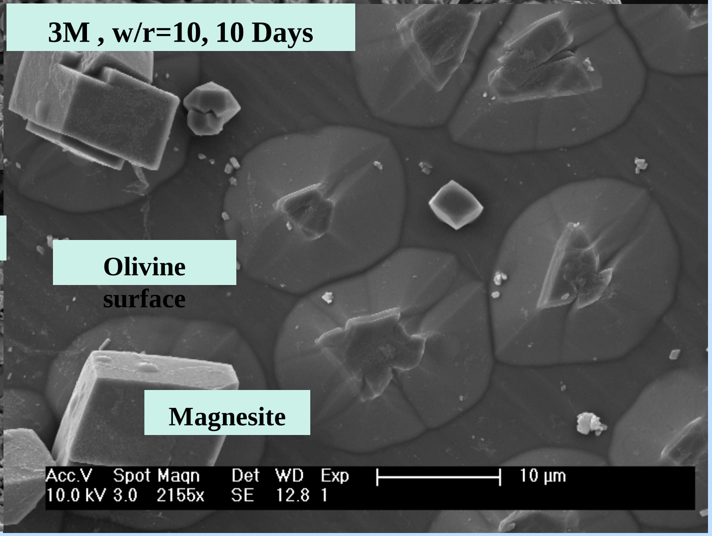
Qiu and Wang 2013, submitted to GCA

Scaling-up: reaction with picrite cube

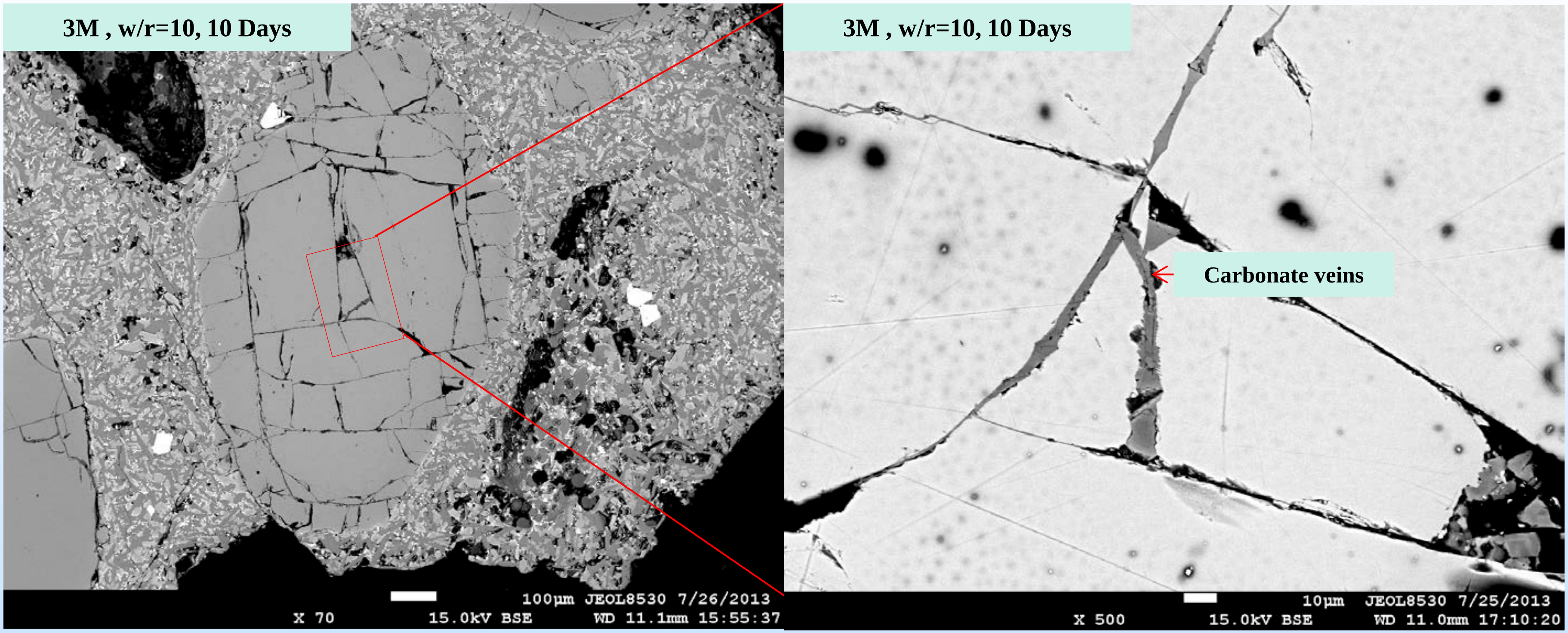

3M , w/r=10, 5 Days


3M , w/r=10, 5 Days


3M , w/r=10, 10 Days


3M , w/r=10, 10 Days

Scaling-up: reaction with picrite cube



The average composition of the carbonate veins:
Mg: 76.1%, Fe: 20.0%, Ca: 3.9% (magnesite)

Also, we see some zonation of the carbonate veins:
Darker core (more Mg) and brighter rim (more Fe)

Crack	Before reaction (µm)	After reaction filled with carbonates (µm)
Wide	3.33	8.75
Middle	1.35	5.03
Narrow	0.45	0.79

Carbonates formed in the olivine cracks could have widened the cracks.

Summary of geochemical result

- Olivine and basalts can form carbonates after reacting with CO_2-containing fluids in our experimental conditions, showing a big CCS potential.
- Reaction rates are faster at higher temperature, higher concentration of DIC in the fluid, and smaller grain-size of crystal.
- Reactions involving olivines are much faster than basalts.
- Carbonation rate after the-first-day reaction for both olivines and basalt determined in our studies is comparable to previous studies, but in our experiments the carbonation reaction for olivines proceeds slowly after the first day.
- The limitation of the carbonation reaction is the production of secondary Mg-bearing silicate minerals, effective removal of SiO_2 from the solution is essential to the carbonation efficiency.
- Basaltic glasses also exhibit fast reaction rate.
- The cracks in olivine grains of picrite chips have been observed to open up after reaction and filled with magnesites.

Geochemical modeling

KINFLOW: Aqueous phase reactive transport model in porous media with **kinetic** control of mineral reactions

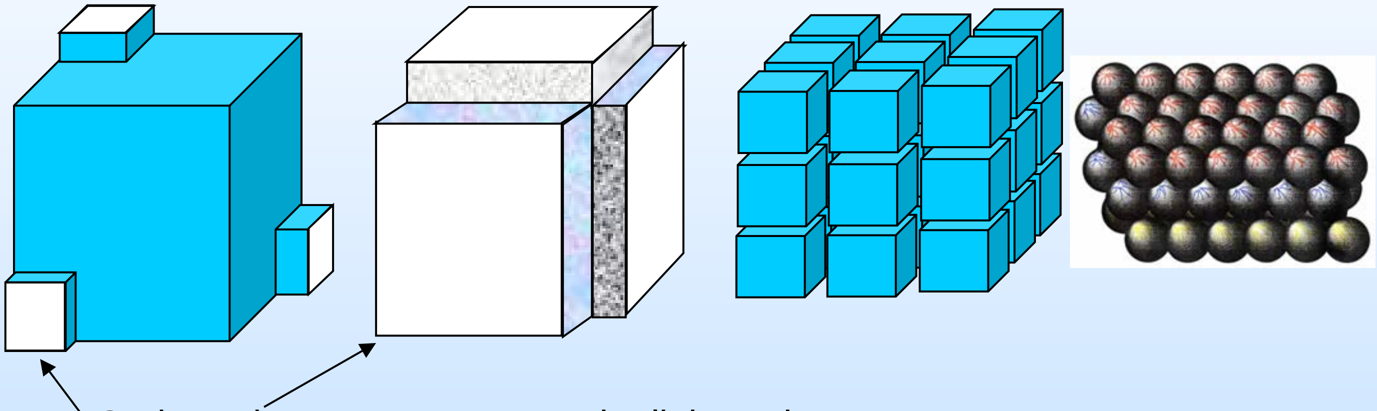
MAIN FEATURES:

- **Aqueous and vapor phase non-isothermal flow and transport**
- **Mineral** dissolutions and precipitation via experimental **kinetics**
- **48 Minerals** covering major rock types and secondary minerals
- **30 Speciation** reactions in solution in **equilibrium** via EQ3/6, from 0-300°C
- **70** Aqueous Species
- **Fe^{3+}/Fe^{2+} Redox** reactions
- **Partitioning** between vapor and aqueous phases (O_2, CO_2, H_2O, …)
- **Injection of fluids**
- **Dynamic porosity evolution. compaction**
- **0D, 1D, 2D**
- Sub-grid-scale **grain models** for mineral surface areas, volumes, porosity

Any rectangular solid prism

Geochemical modeling

Grain models



Grain-grain contact areas are the light end caps

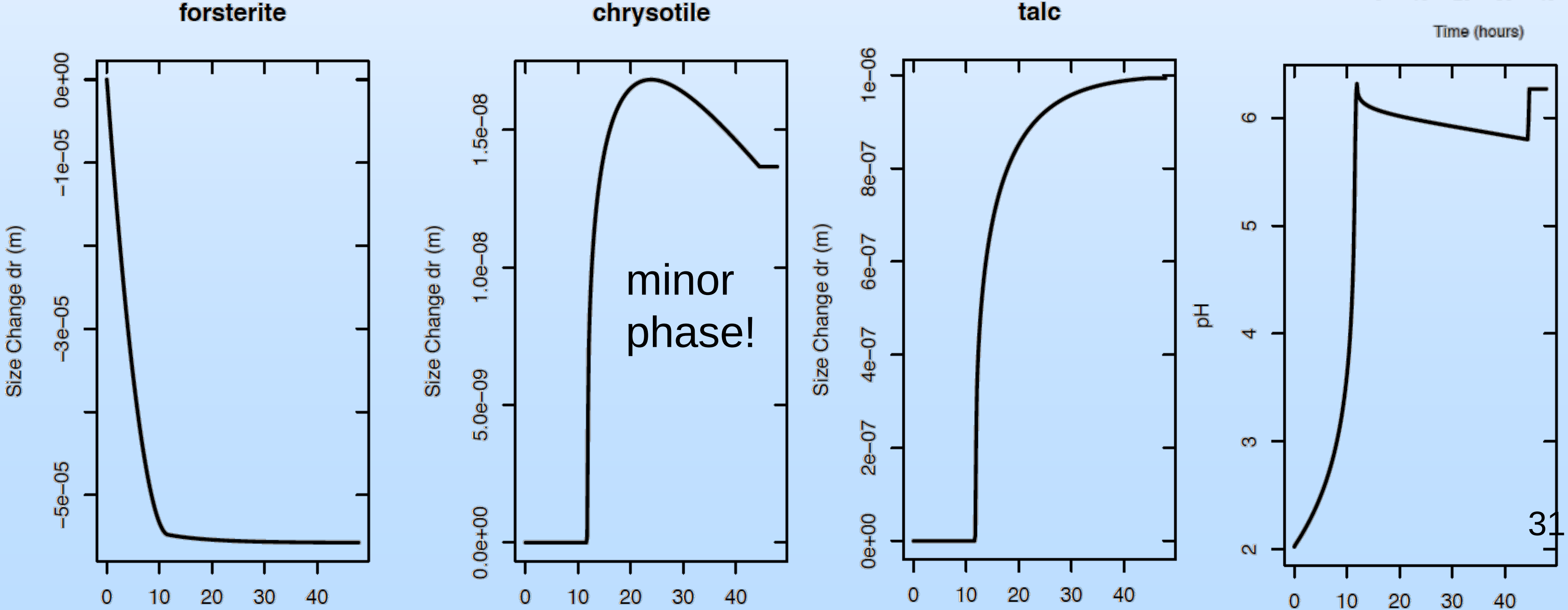
Grain model parameters for fluid flow and mineral reaction kinetics: Grain volumes, spacing, porosity, surface areas, fluid gap spacing, and the permeability.

Geochemical modeling

Example for dissolution reaction

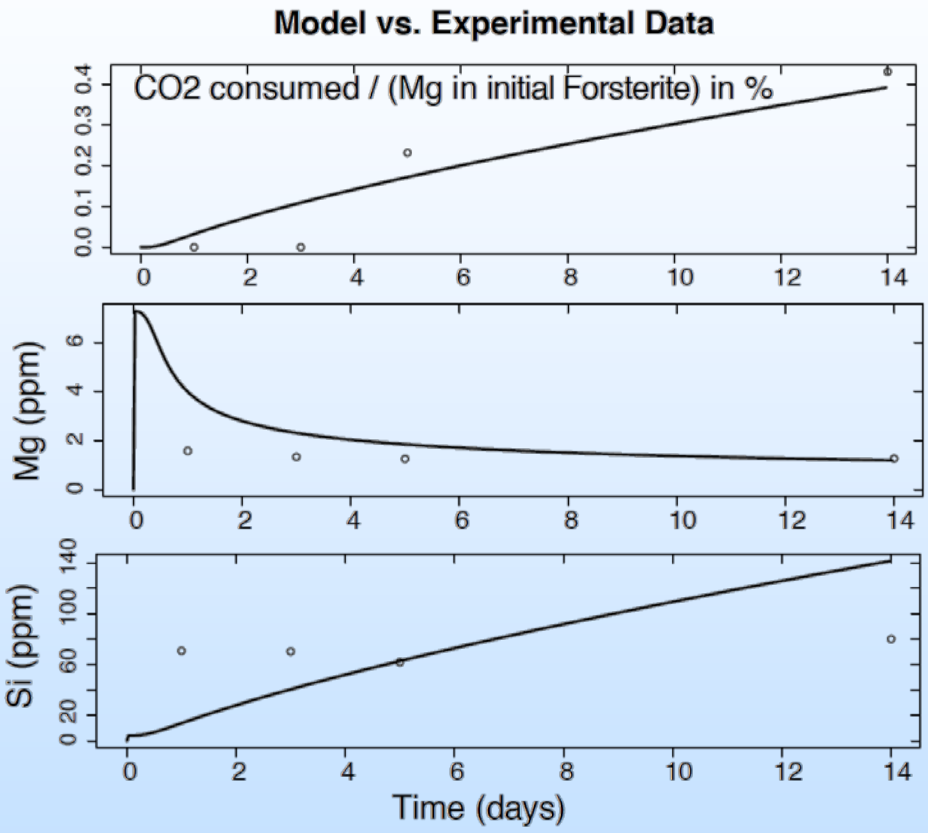
- Full model (KINFLOW) with Palandri and Kharaka (2004) rates
- Forsterite single crystal dissolution at 100^{o}C in a closed system

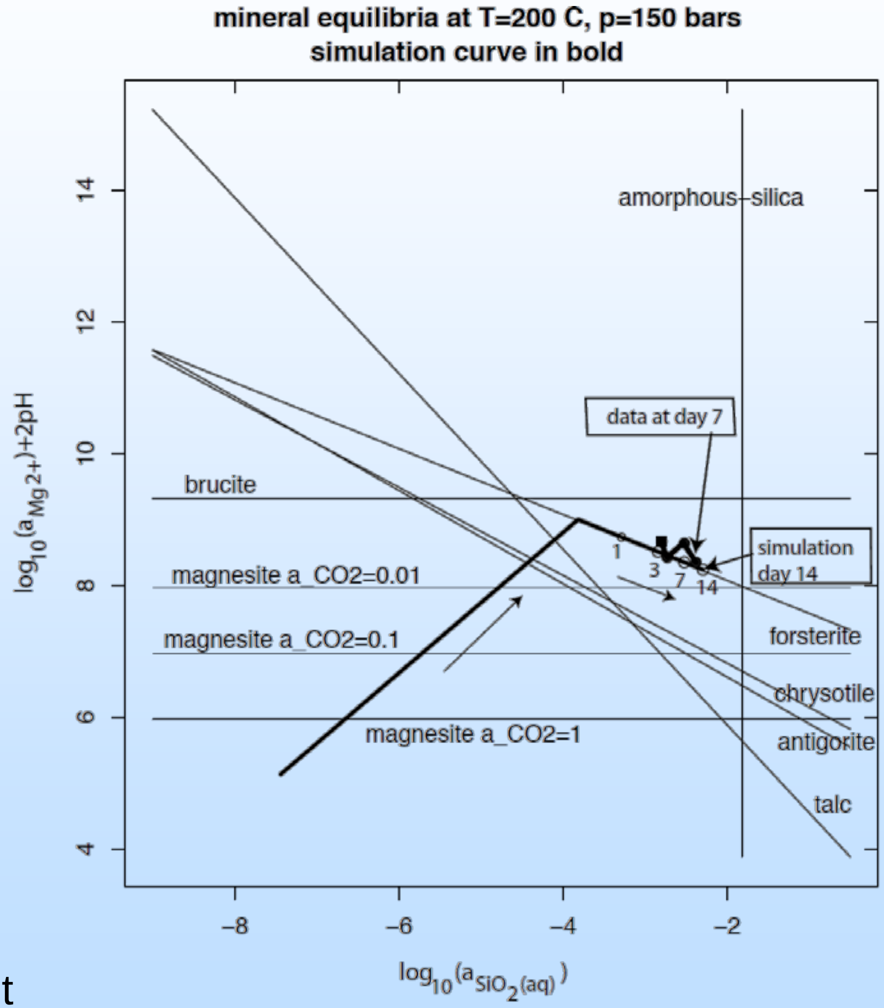
Temperature ramp



minor phase!

Geochemical modeling





Olivine grain, 1 M $NaHCO_3$, 200 °C and 150 bar

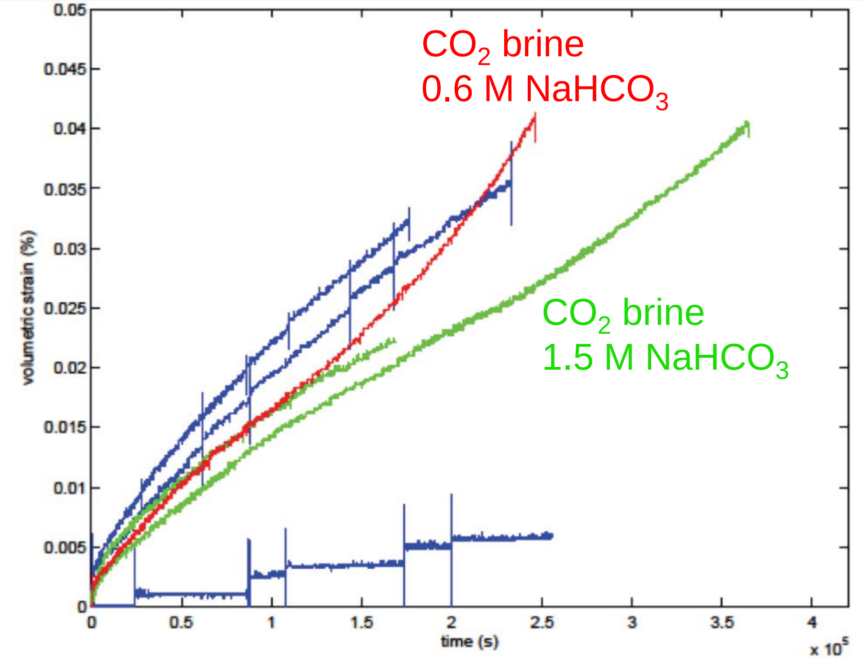
Using magnesite precipitation kinetics from Saldi et al., (2010, 2012)

Geo-mechanical experiment and modeling

Reactive Flow Combined with Deformation

Dunite (olivine) samples saturated with different pore fluids are subjected to hydrostatic compaction (5 MPa, 150°C), followed by longitudinal deformation at constant strain rate. Samples reacted with CO_2 brine show an acceleration of strain at late times.

University of Maryland



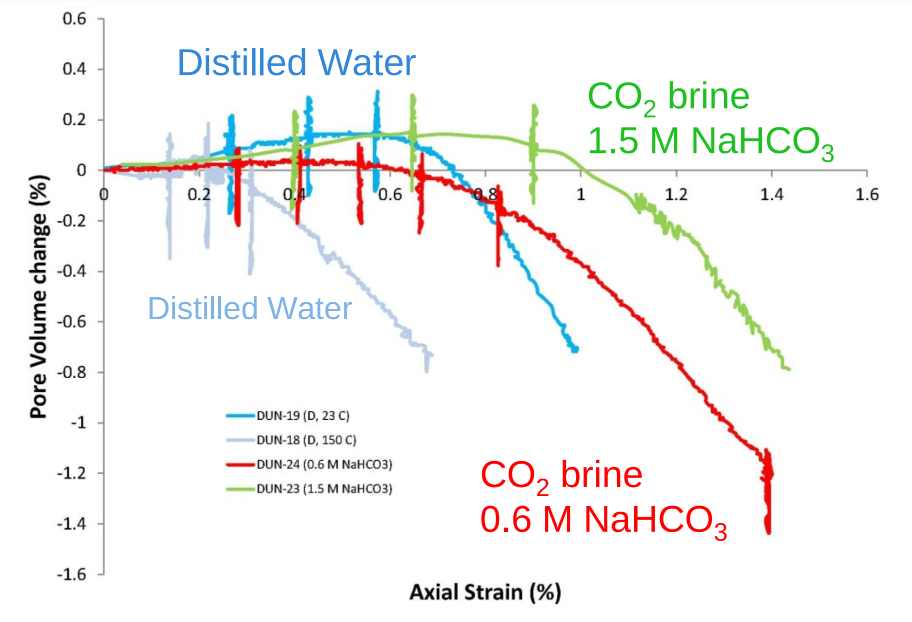
Volumetric strain curve fit with a
hybrid creep model with 2 time scales (Main, 2000)

Geo-mechanical experiment and modeling

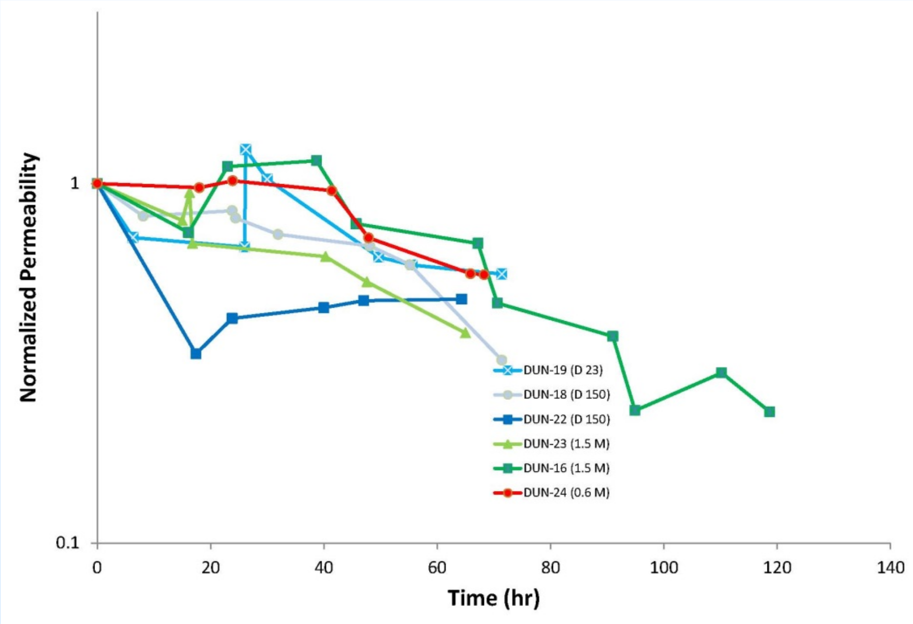
Reactive Flow Combined with Deformation

Dunite (olivine) samples saturated with different pore fluids are subjected to hydrostatic compaction (5 MPa, 150°C), followed by longitudinal deformation at constant strain rate.

Samples reacted with CO_2 brine accommodate more shortening before dilation and failure.



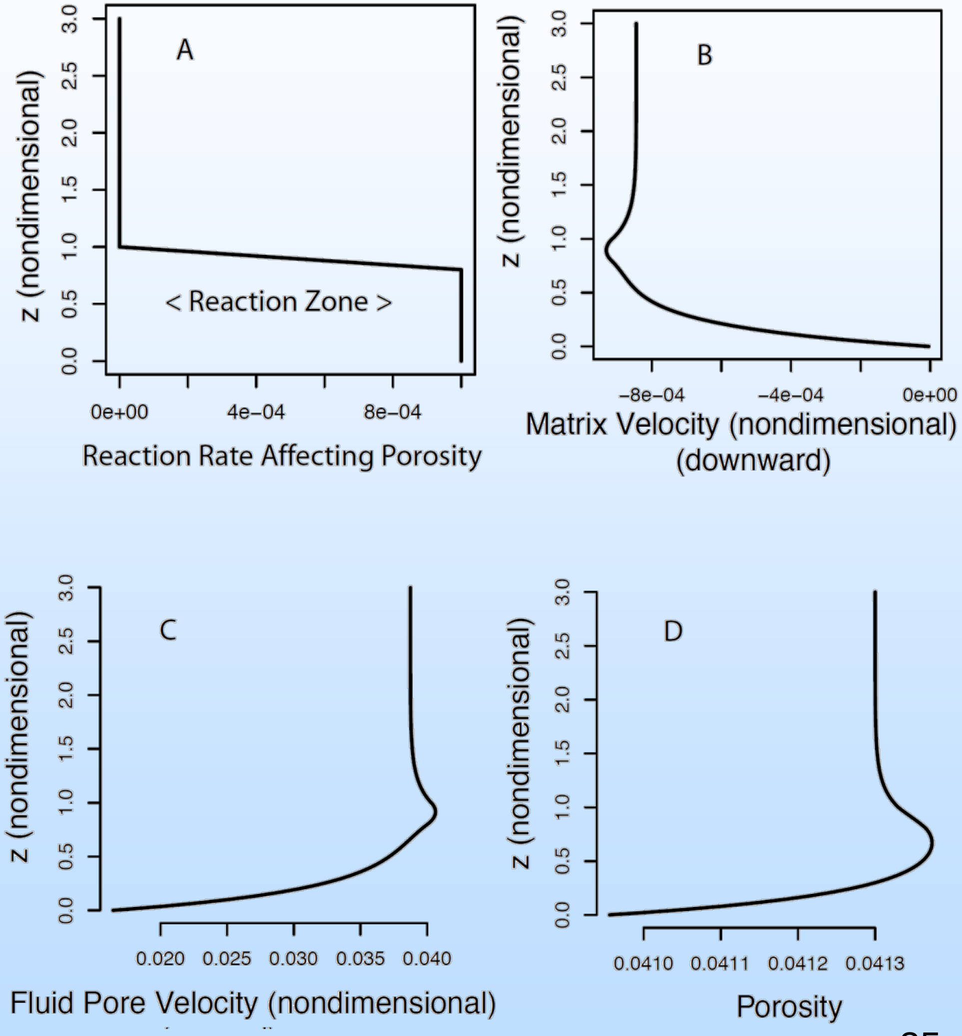
Pore volume change versus time for hydrostatic creep tests



Permeability versus time for strain for hydrostatic creep tests
(starting permeability = 1)

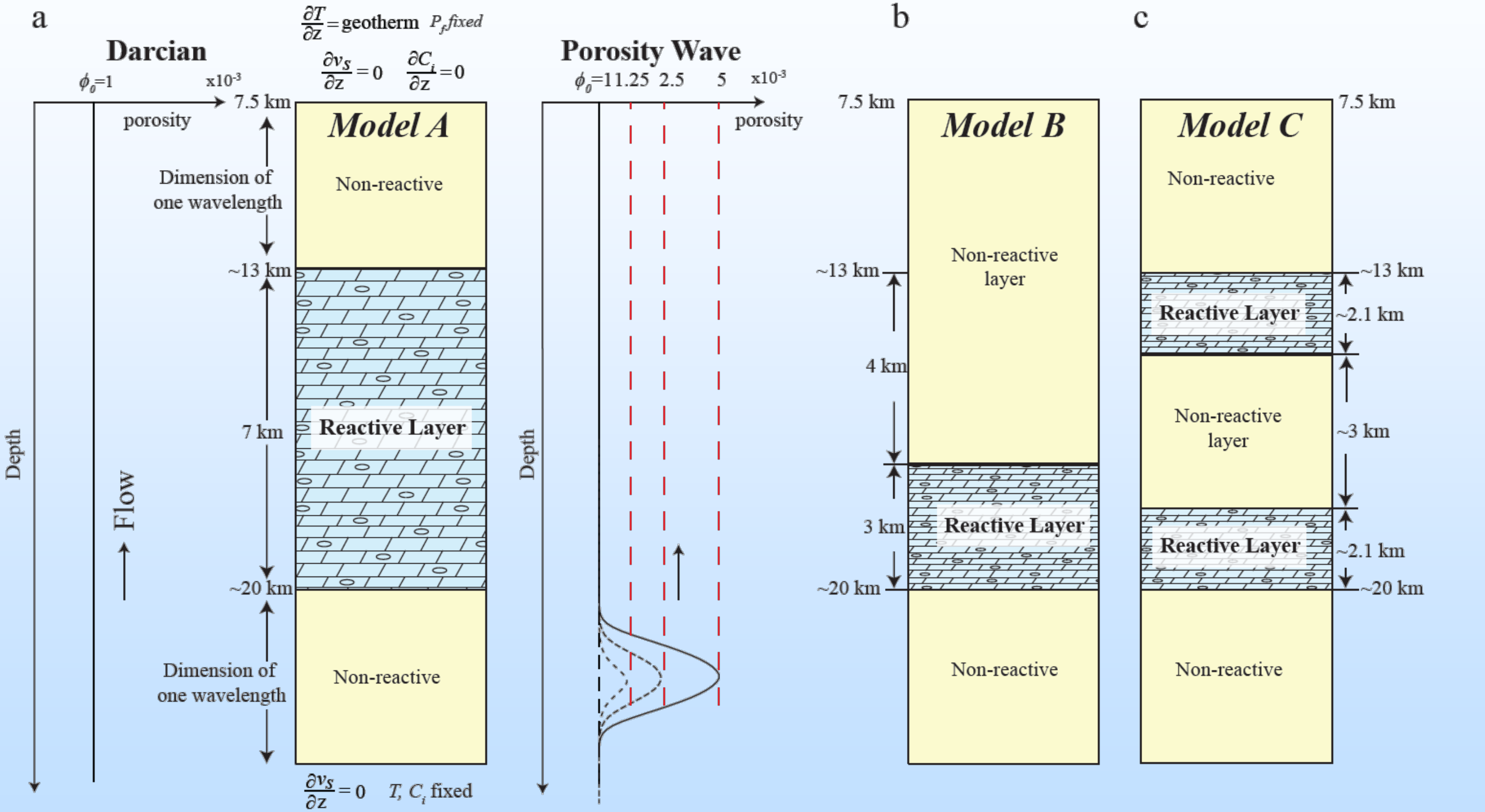
Geomechanical modeling: compaction

One-dimensional formulation for compaction of the solid phase with reactions between the solid and liquid phases



Cai et al., 2013

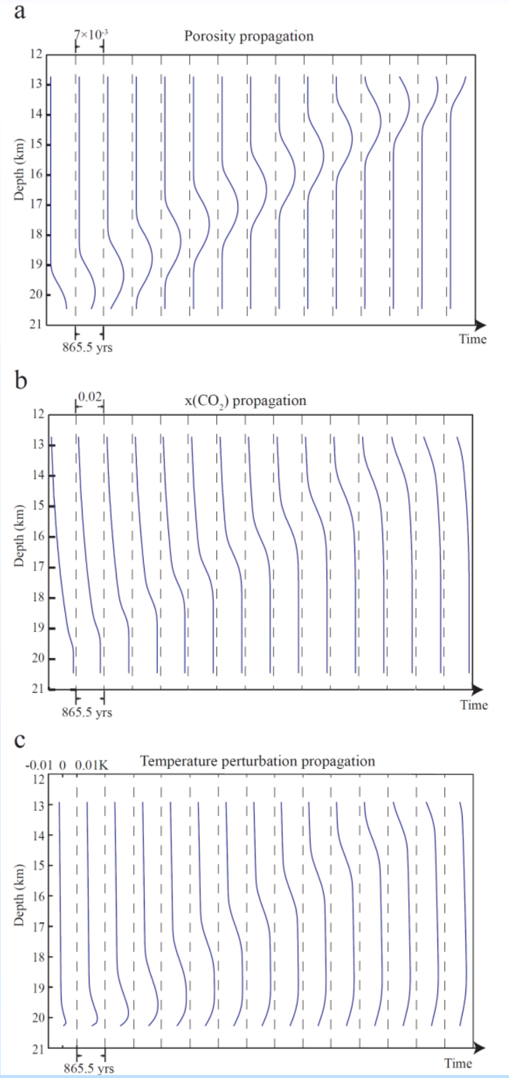
Geomechanical modeling: porosity wave

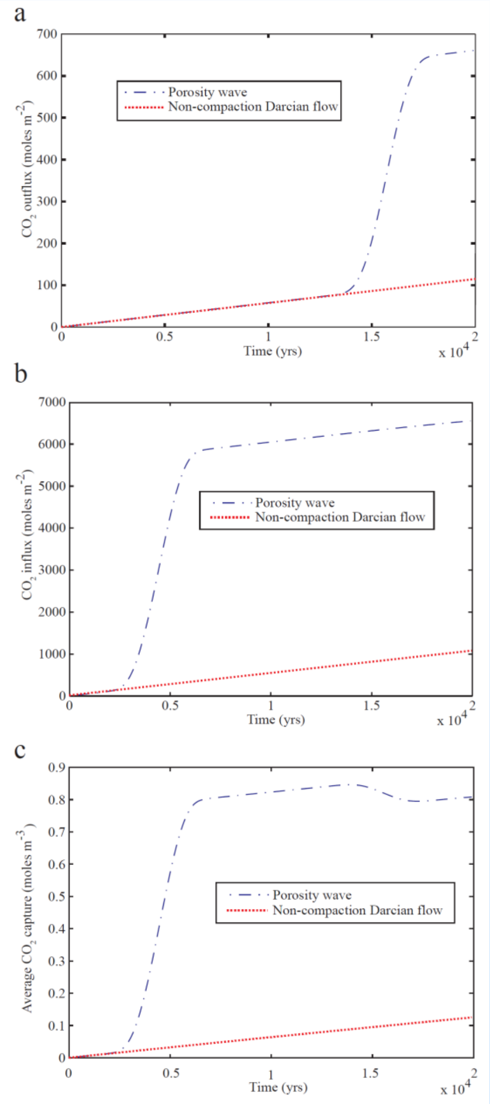


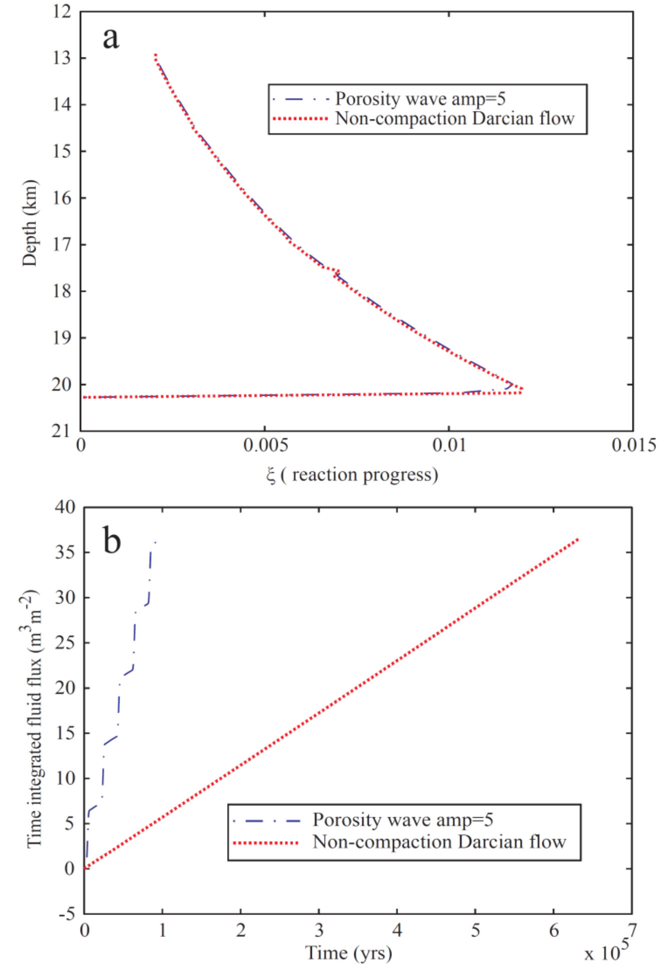
$$7CO_2 + 3Calcite + Tremolite = 5Dolomite + 8Quartz + H_2O$$

Meng and Ague 2013, submitted to EPSL

Geomechanical modeling: porosity wave

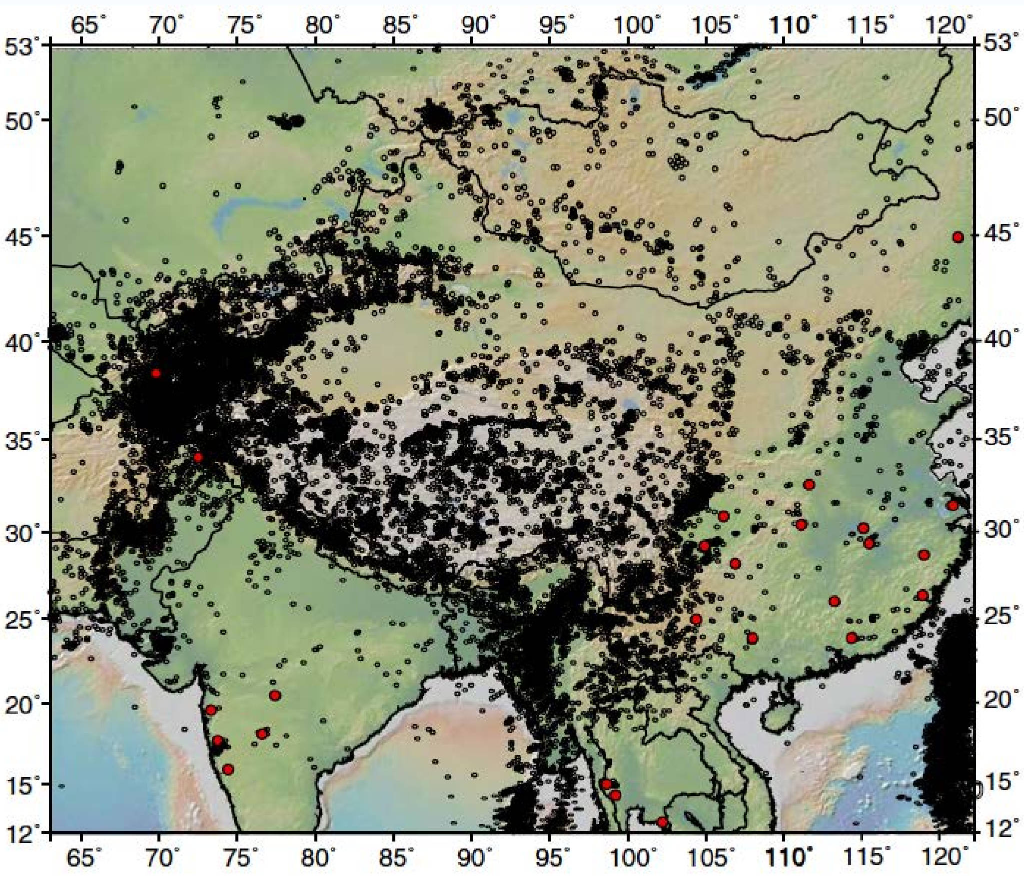




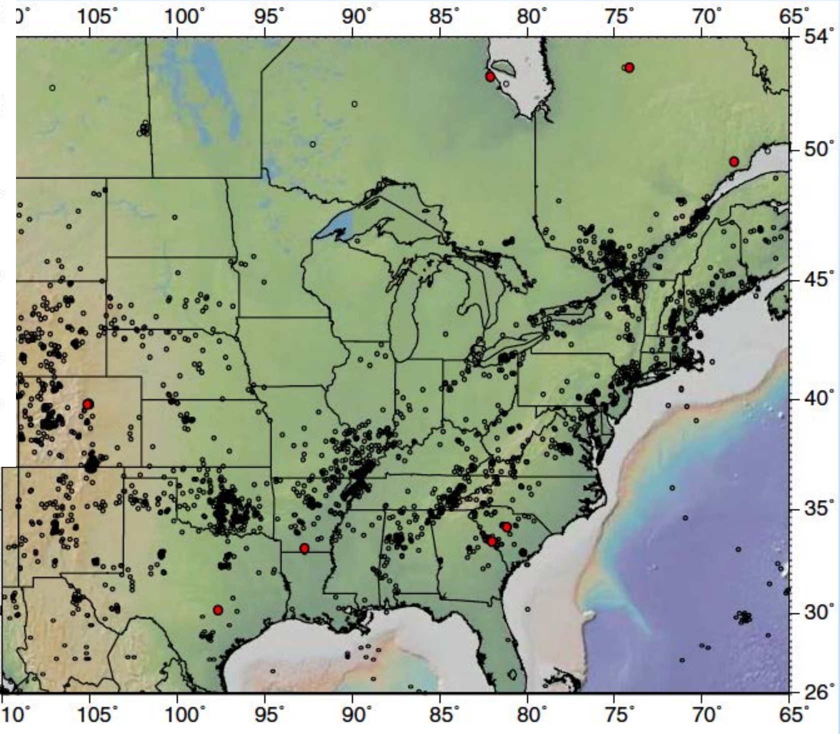


Meng and Ague 2013, submitted to EPSL

Mineral carbon sequestration and induced seismicity

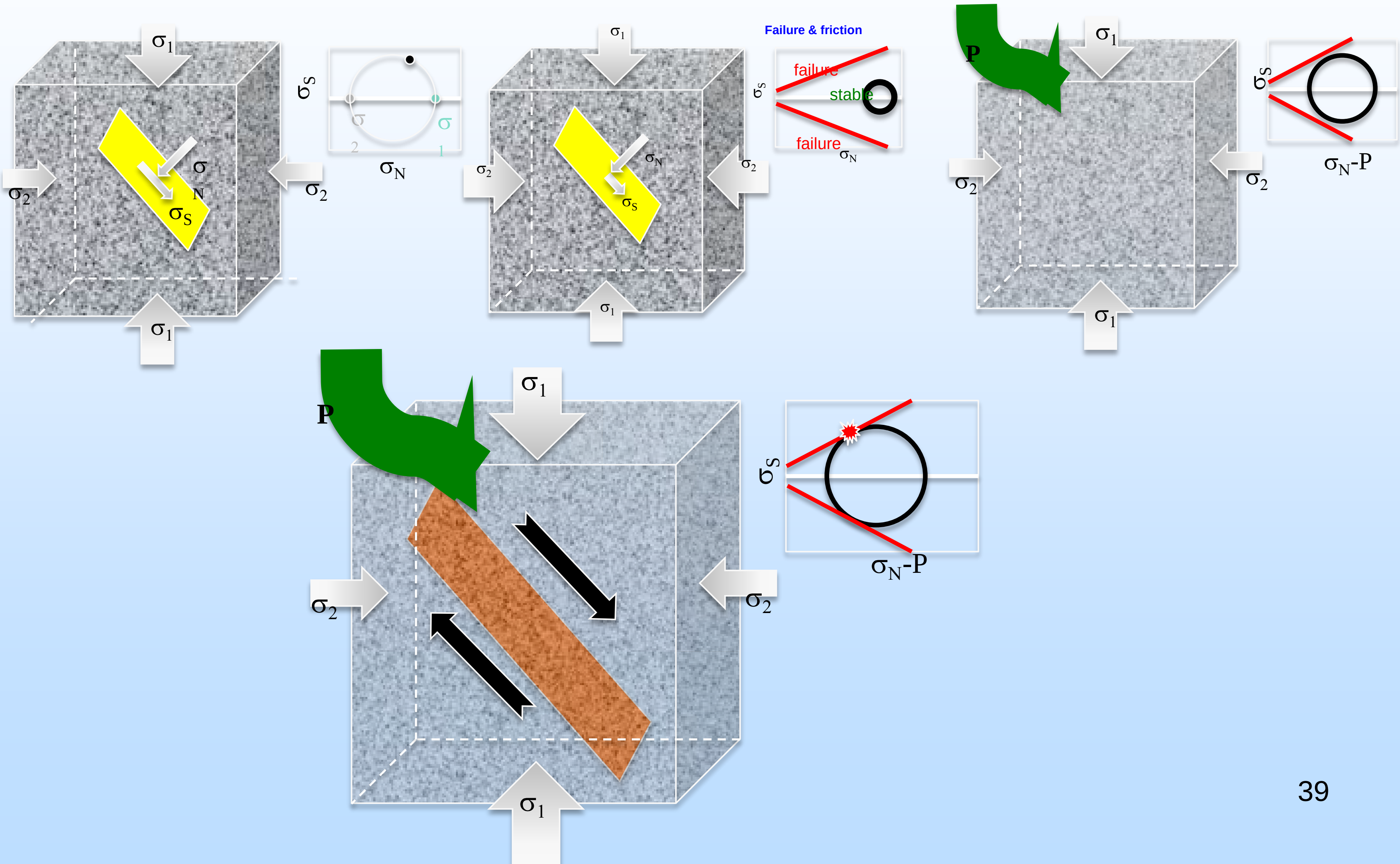


Instrumentally recorded seismicity of south and east Asia, central and eastern United States and southeastern Canada. Red dots indicate sites of reservoir-induced seismicity.



CCS fluid injection needed to offset CO_2 emissions would trigger at least low level of seismicity and compromise cap rock - Zoback & Gorelick, PNAS, 2012

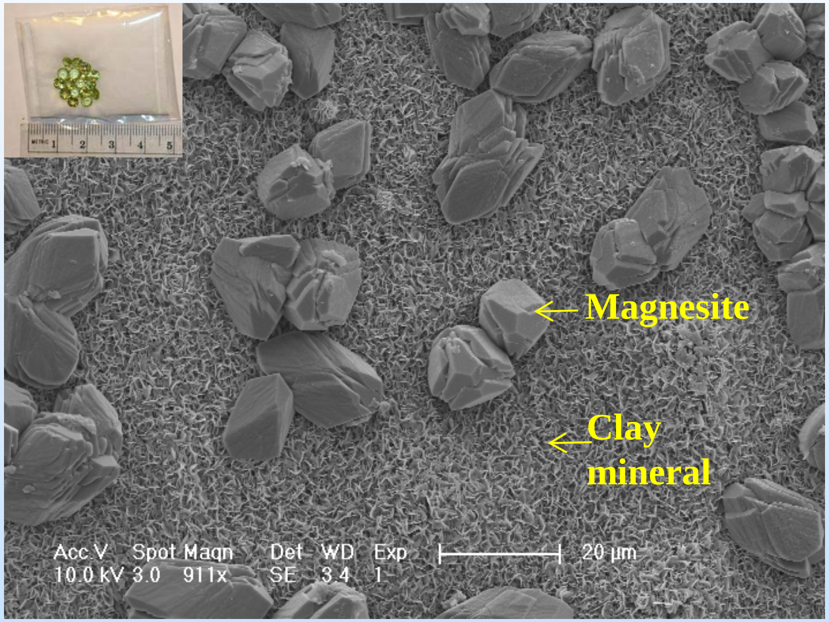
Mineral carbon sequestration and induced seismicity



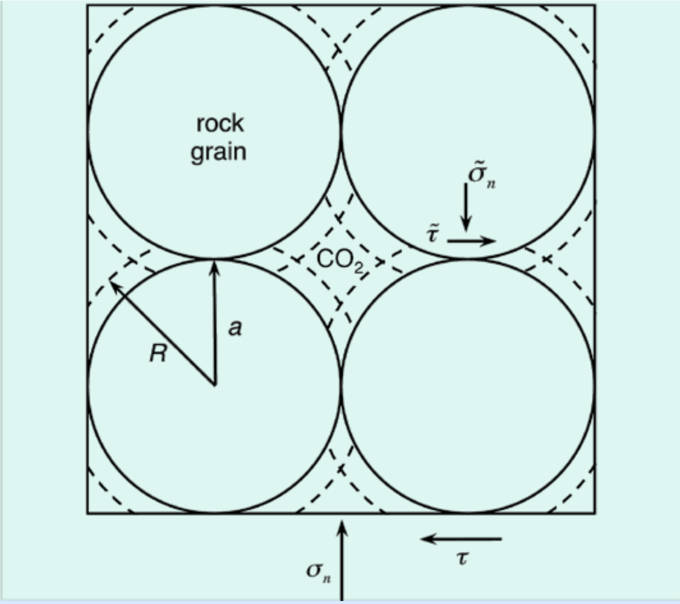
Mineral carbonation in mafic rocks

Carbonation of olivine:

$$Mg_2SiO_4 + CO_2 = 2\,MgCO_3 + SiO_2$$

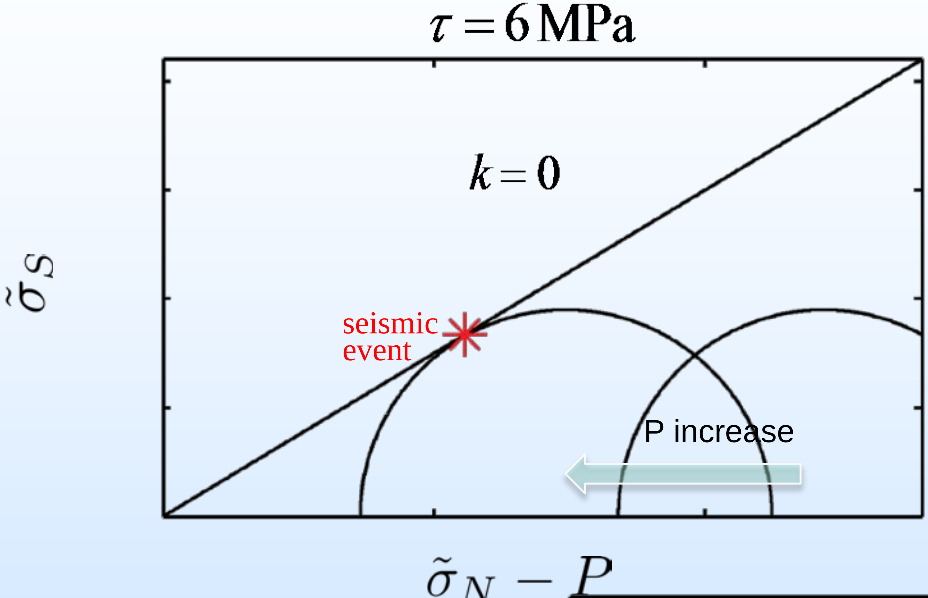


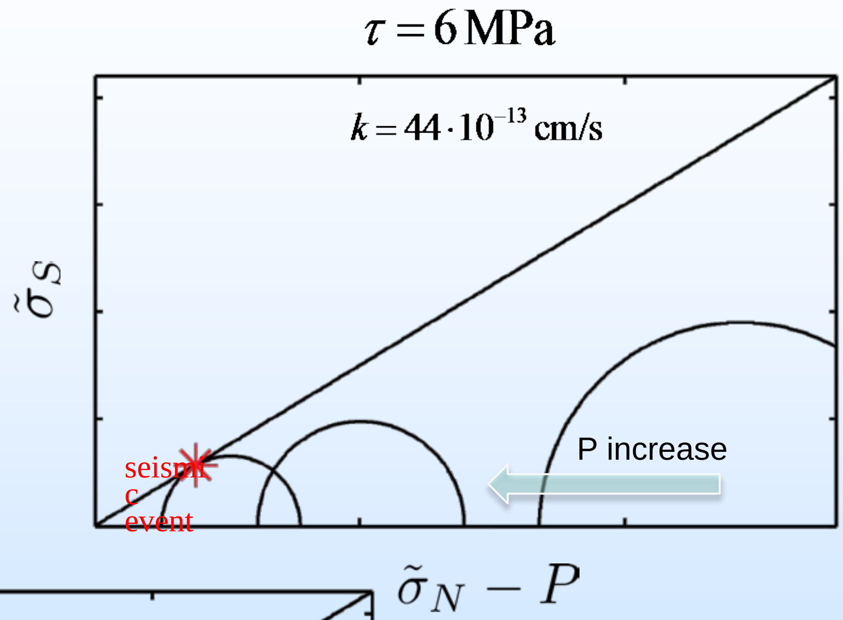
The surface of an olivine grain (from San Carlos) after the carbonation reaction at 200°C,1650 psi for 3 days in 0.45 ml of 1M $NaHCO_3$

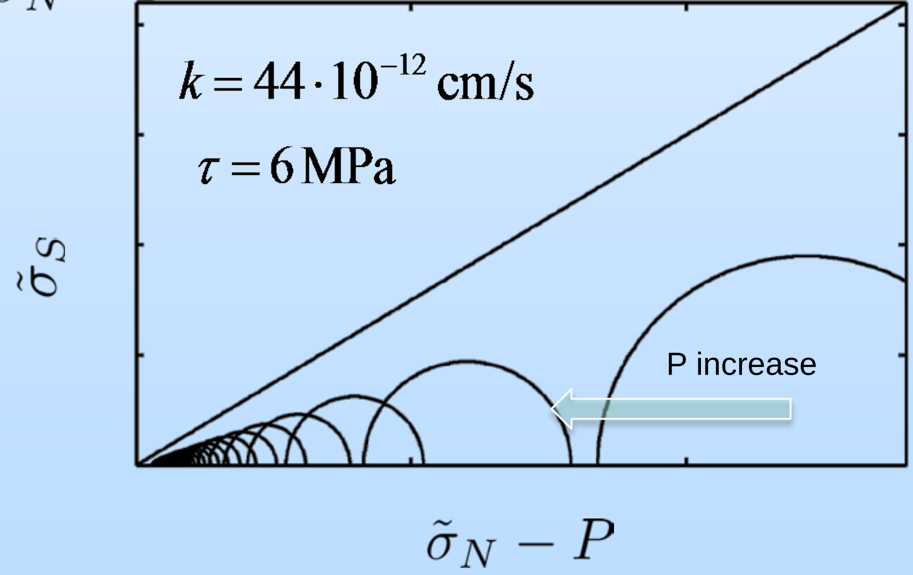


- Carbonates take more volume: Grains grow
- Larger grain-grain contact distributes load, reduces local stress
- Smaller grain-fluid contact reduces effect of pore pressure

Mineral carbonation in mafic rocks







Summary for Geomechanical modeling

- Mineral sequestration can potentially reduce seismic risk provided fluid pumping rates do not exceed a critical value
- Mineral and grain growth stores CO_2 and offsets stress loads
- Caveat: it also armors grains surfaces, fills pores and chokes off permeable pathways
  - So opening of new surfaces and permeability still requires some level of fracturing, e.g., either reaction driven or hydraulic

Accomplishments to Date

- Reaction kinetics between CO_2-bearing fluids and olivine has been investigated as a function of surface area, chemistry of CO_2-bearing fluid, fluid/olivine ratio and experimental duration (Yale U).
  - The olivine mineral fraction converted to carbonate (carbonation fraction), generally reaches an upper limit and then decreases, as conditions favorable to the formation of secondary magnesium minerals consume magnesite.
  - An empirical formula for the maximum carbonation fraction that can be achieved by reacting CO_2-bearing fluid and olivine was has been determined.
  - A reaction-rate model that fits experiments with olivine crystals, with the major species in solution, has been developed from first principles.
- A similar , but less comprehensive set of experiments has been carried out on natural basaltic rock samples collected from different volcanoes on the Big Island in Hawai’i and characterized at U Hawai’i.

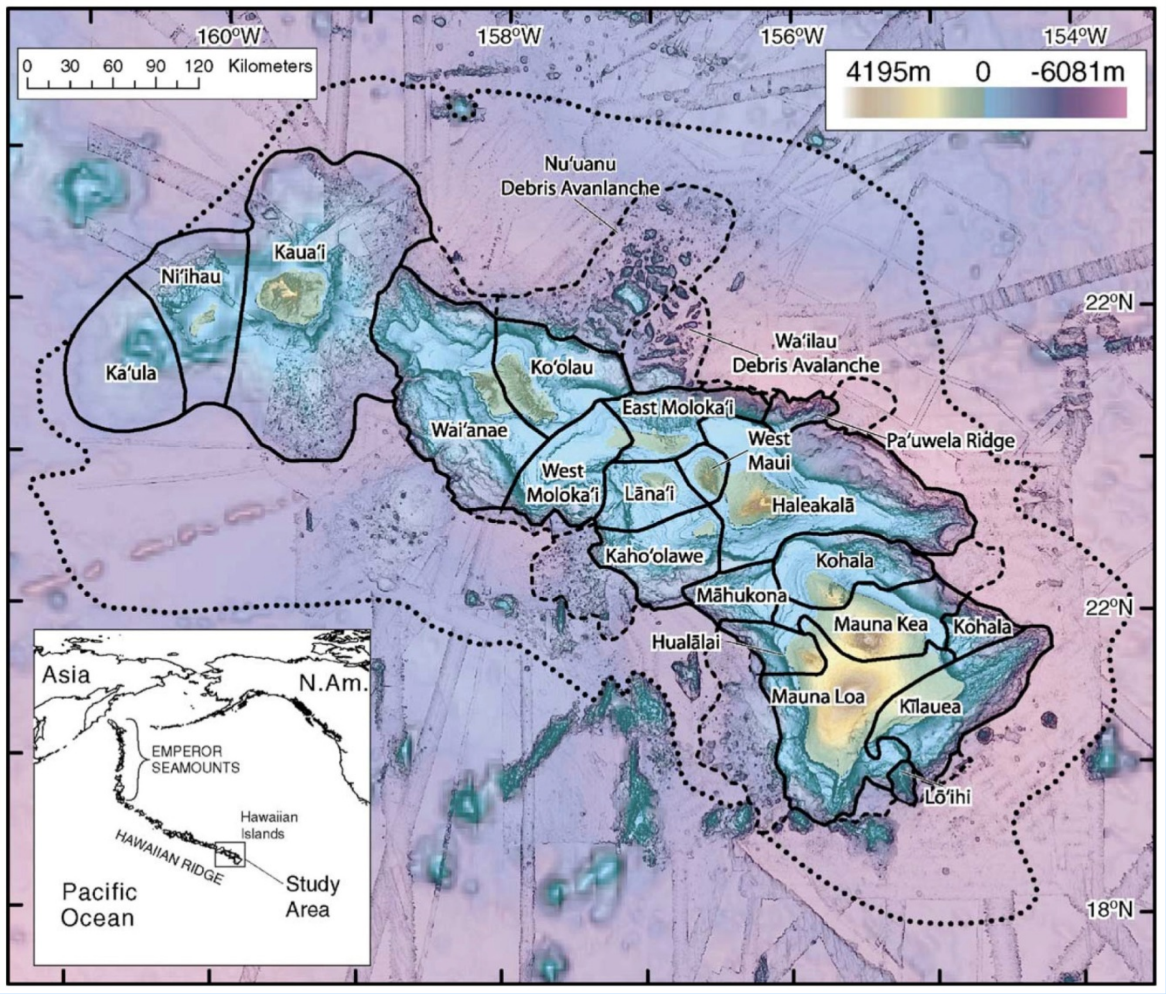
Accomplishments to Date

- A new apparatus was developed for geomechanical experiments involving reactive transport and deformation (U Maryland).
  - A series of experiments involving hydrostatic compaction followed by constant strain-rate deformation was performed on thermally cracked dunite samples saturated with carbon-dioxide brines of varying composition. Permeability was monitored in situ during the experiments.
  - Comparison of the samples' volume changes to their axial strains (shortening) suggests that samples reacting with CO2 saturated brines can accommodate more shortening, before the onset of dilation (swelling) and failure, than samples reacted with distilled water.
- Models of combined reactive flow and deformation have been developed and applied to (1) 1D geomechanical experiments, (2) mineral carbonation and induced seismicity, and (3) porosity waves involving transport of CO_2.

Future directions

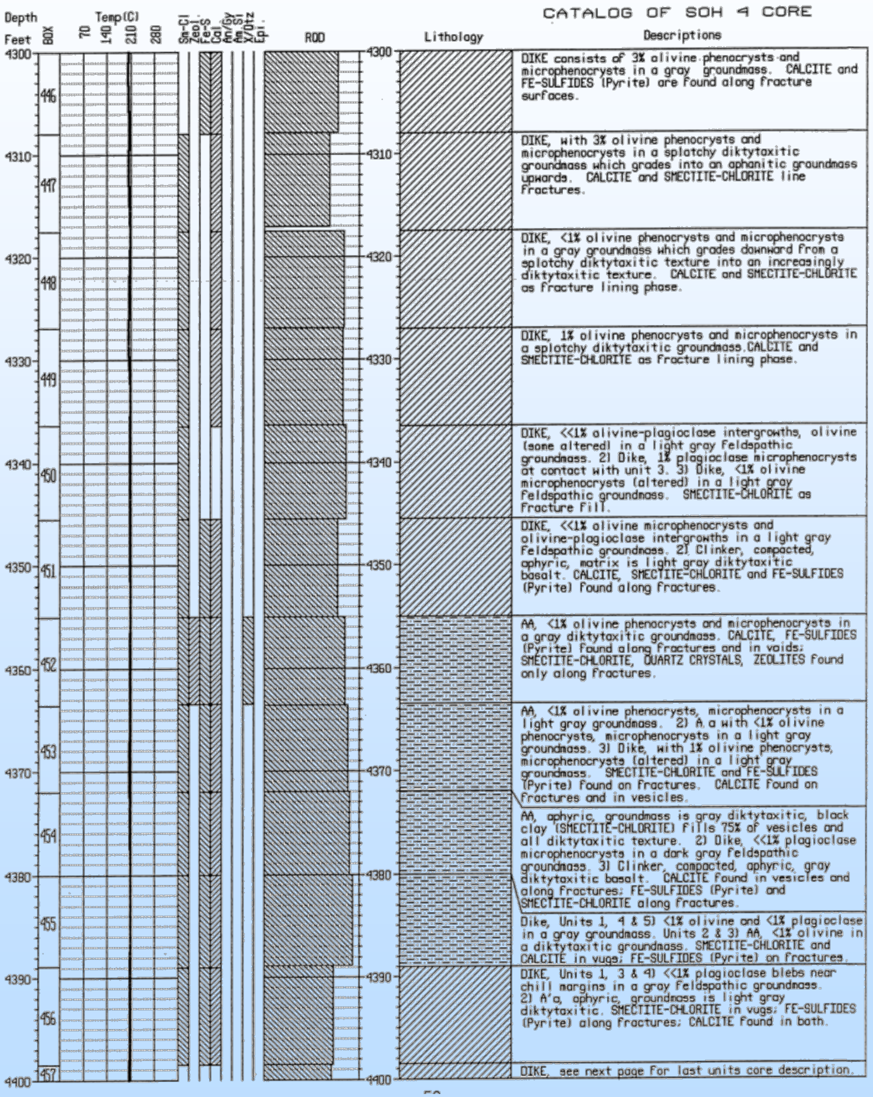
- Finish compilation and publication of the database of thermodynamic parameters for mineral carbonation reactions (reaction-rate table).
- Finish development of multi-dimensional flow and deformation codes.
- Further geochemical experiments with natural rock samples in a new autoclave (Yale) that allows better monitoring of experimental conditions over the course of the reaction.
- Further geomechanical experiments using microtomography to image the evolution of pore space during flow and deformation.

Future directions



Map of combined seafloor bathymetry and subaerial topography of the shield volcanoes that make up the Hawaiian Islands. The total volume of the Hawaiian Islands volcanic edifices from base to summit and primarily olivine basalt (solid outlines), is **527,200** km^3. This volume of basalt is comparable to other large igneous provinces such as the Deccan Traps in India, and is 3x the volume of the Columbia River Basalts in Washington, Idaho, and Oregon, where CO$_2$ injection is currently underway. *We estimate that the Hawaiian Ridge igneous province can store about* ***2.6 x*** $\boldsymbol{10^{17}}$ ***kg*** *CO*$_2$*, or approximately 400 times the post-industrialization anthropogenic* *CO*$_2$ *production (IPCC, 2007).*

Phase 2: Kilauea Scientific Observation Hole Cores (SOH)



CATALOG OF SOH 4 CORE

Descriptions

DIKE consists of 3% olivine phenocrysts and microphenocrysts in a gray groundmass. CALCITE and FE-SULFIDES (Pyrite) are found along fracture surfaces.

DIKE, with 3% olivine phenocrysts and microphenocrysts in a splotchy diktytaxitic groundmass which grades into an aphanitic groundmass upwards. CALCITE and SMECTITE-CHLORITE line fractures.

DIKE, <1% olivine phenocrysts and microphenocrysts in a gray groundmass which grades downward from a splotchy diktytaxitic texture into an increasingly diktytaxitic texture. CALCITE and SMECTITE-CHLORITE as fracture lining phase.

DIKE, 1% olivine phenocrysts and microphenocrysts in a splotchy diktytaxitic groundmass.CALCITE and SMECTITE-CHLORITE as fracture lining phase.

DIKE, <<1% olivine-plagioclase intergrowths, olivine (some altered) in a light gray feldspathic groundmass. 2) Dike, 1% plagioclase microphenocrysts at contact with unit 3. 3) Dike, <1% olivine microphenocrysts (altered) in a light gray feldspathic groundmass. SMECTITE-CHLORITE as fracture fill.

DIKE, <<1% olivine microphenocrysts and olivine-plagioclase intergrowths in a light gray feldspathic groundmass. 2) Clinker, compacted, aphyric, matrix is light gray diktytaxitic basalt. CALCITE, SMECTITE-CHLORITE and FE-SULFIDES (Pyrite) found along fractures.

AA, <1% olivine phenocrysts and microphenocrysts in a gray diktytaxitic groundmass. CALCITE, FE-SULFIDES (Pyrite) found along fractures and in voids; SMECTITE-CHLORITE, QUARTZ CRYSTALS, ZEOLITES found only along fractures.

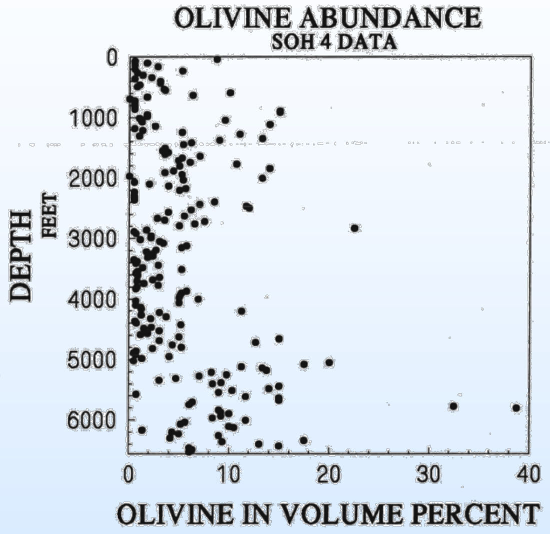
AA, <1% olivine phenocrysts, microphenocrysts in a light gray groundmass. 2) A a with <1% olivine phenocrysts, microphenocrysts in a light gray groundmass. 3) Dike, with 1% olivine phenocrysts, microphenocrysts (altered) in a light gray groundmass. SMECTITE-CHLORITE and FE-SULFIDES (Pyrite) found on fractures. CALCITE found on fractures and in vesicles.

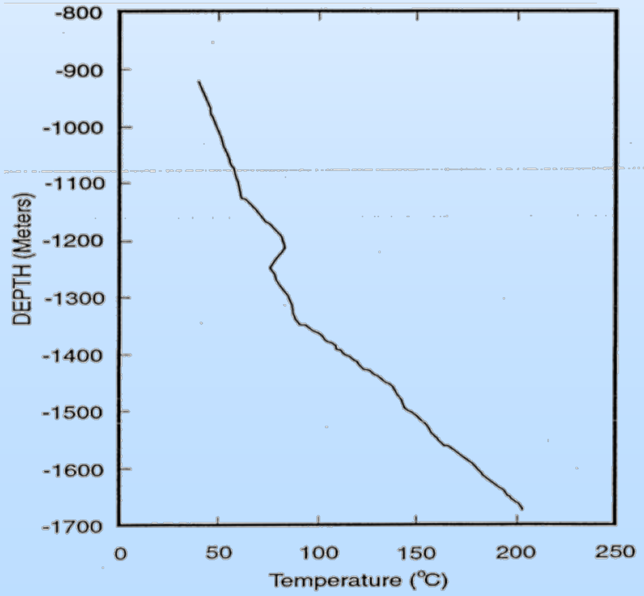
AA, aphyric, groundmass is gray diktytaxitic, black clay (SMECTITE-CHLORITE) fills 75% of vesicles and all diktytaxitic texture. 2) Dike, <<1% plagioclase microphenocrysts in a dark gray feldspathic groundmass. 3) Clinker, compacted, aphyric, gray diktytaxitic basalt. CALCITE found in vesicles and along fractures; FE-SULFIDES (Pyrite) and SMECTITE-CHLORITE along fractures.

Dike, Units 1, 4 & 5) <1% olivine and <1% plagioclase in a gray groundmass. Units 2 & 3) AA, <1% olivine in a diktytaxitic groundmass. SMECTITE-CHLORITE and CALCITE in vugs; FE-SULFIDES (Pyrite) on fractures.

DIKE, Units 1, 3 & 4) <<1% plagioclase blebs near chill margins in a gray feldspathic groundmass. 2) A'a, aphyric, groundmass is light gray diktytaxitic. SMECTITE-CHLORITE in vugs; FE-SULFIDES (Pyrite) along fractures; CALCITE found in both.

DIKE, see next page for last units core description.





(Figures from USGS Open-file Reports)

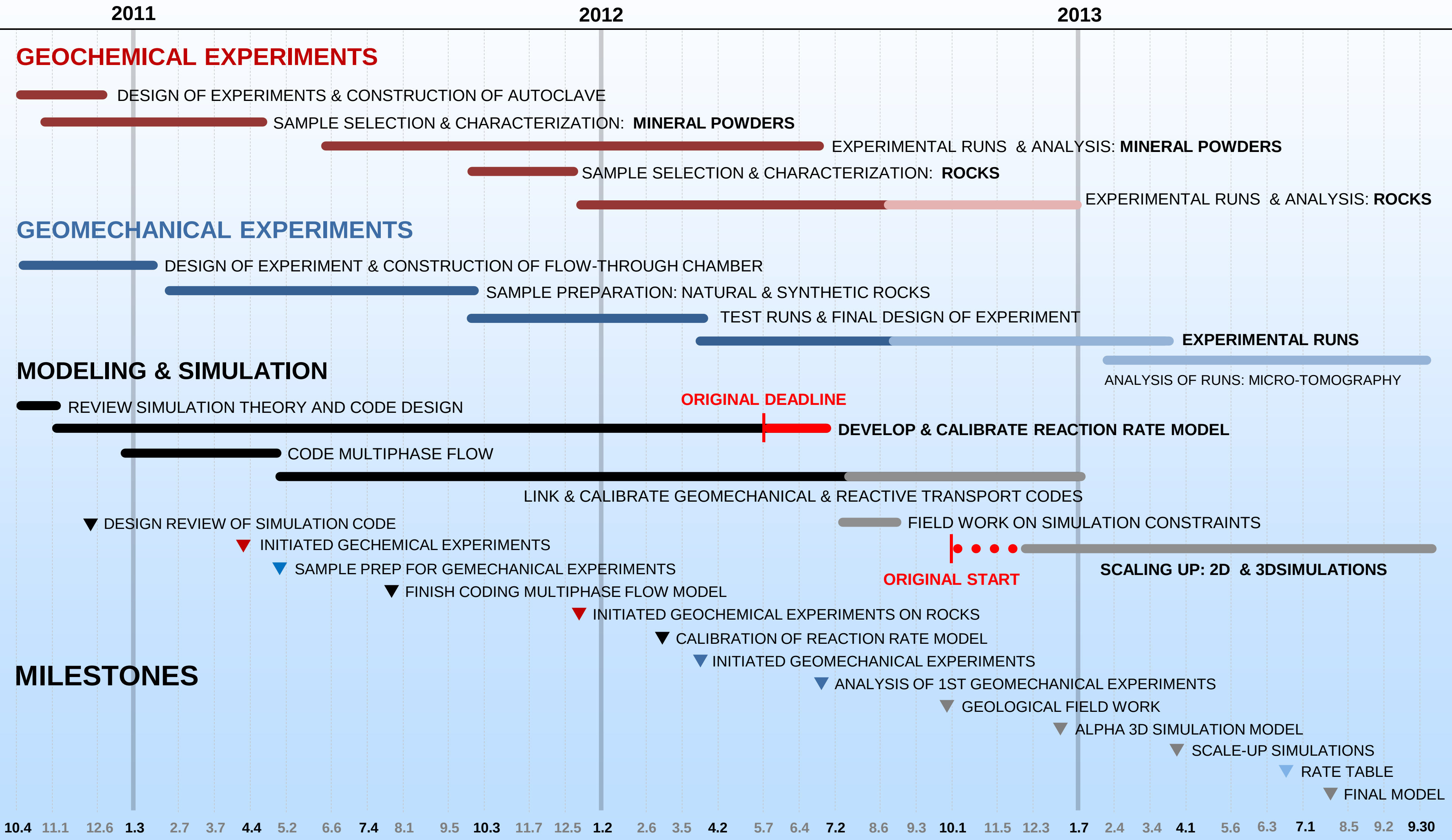
Appendix

1. Organization
2. Gantt chart
3. Bibliography

Organization

- There are 9 principal investigators (PIs) at 3 academic institutions:
  - 6 at Yale University,
  - 1 at University of Maryland College Park, and
  - 2 at University of Hawai'i at Mānoa.
- Yale is lead contractor, with subs to Maryland & Hawai'i
  - **Geochemical experiments** are carried out in a special high-P/T laboratory at Yale West Campus
  - **Geomechanical experiments** are carried out in a reactive flow-through apparatus at Department of Geology, U Maryland
  - **Collection and analysis of field samples** for experiments is done by through Department of Geology & Geophysics, U Hawai'i
  - **Development of theory and simulation codes** is done at Department of Geology & Geophysics, Yale U

Gantt Chart



GEOCHEMICAL EXPERIMENTS

DESIGN OF EXPERIMENTS & CONSTRUCTION OF AUTOCLAVE

SAMPLE SELECTION & CHARACTERIZATION: **MINERAL POWDERS**

EXPERIMENTAL RUNS & ANALYSIS: **MINERAL POWDERS**

SAMPLE SELECTION & CHARACTERIZATION: **ROCKS**

EXPERIMENTAL RUNS & ANALYSIS: **ROCKS**

GEOMECHANICAL EXPERIMENTS

DESIGN OF EXPERIMENT & CONSTRUCTION OF FLOW-THROUGH CHAMBER

SAMPLE PREPARATION: NATURAL & SYNTHETIC ROCKS

TEST RUNS & FINAL DESIGN OF EXPERIMENT

EXPERIMENTAL RUNS

ANALYSIS OF RUNS: MICRO-TOMOGRAPHY

MODELING & SIMULATION

REVIEW SIMULATION THEORY AND CODE DESIGN

ORIGINAL DEADLINE

DEVELOP & CALIBRATE REACTION RATE MODEL

CODE MULTIPHASE FLOW

LINK & CALIBRATE GEOMECHANICAL & REACTIVE TRANSPORT CODES

FIELD WORK ON SIMULATION CONSTRAINTS

ORIGINAL START

SCALING UP: 2D & 3DSIMULATIONS

MILESTONES

- ▼ DESIGN REVIEW OF SIMULATION CODE
- ▼ INITIATED GECHEMICAL EXPERIMENTS
- ▼ SAMPLE PREP FOR GEMECHANICAL EXPERIMENTS
- ▼ FINISH CODING MULTIPHASE FLOW MODEL
- ▼ INITIATED GEOCHEMICAL EXPERIMENTS ON ROCKS
- ▼ CALIBRATION OF REACTION RATE MODEL
- ▼ INITIATED GEOMECHANICAL EXPERIMENTS
- ▼ ANALYSIS OF 1ST GEOMECHANICAL EXPERIMENTS
- ▼ GEOLOGICAL FIELD WORK
- ▼ ALPHA 3D SIMULATION MODEL
- ▼ SCALE-UP SIMULATIONS
- ▼ RATE TABLE
- ▼ FINAL MODEL

Bibliography

- Three submitted manuscripts under review
  - “Mg isotope fractionation during olivine dissolution”, Lin Qiu and Zhengrong Wang, submitted to GCA.
  - “Experimental Study of the Reaction Kinetics Between CO_2-Bearing Fluid and Olivine”, Qiu et al., submitted to *Chemical Geology*.
  - “The Impact of Porosity Waves on Crustal Reaction Progress and CO_2 Mass Transfer”, Tian M and Ague J, submitted to *Earth and Planetary Science Letters*.
- Three Peer-reviewed publications published at this time
  - “Mineral Carbon Sequestration and Induced Seismicity,” Yarushina and Bercovici, *Geophysical Research Letters* **40**, 2013, 814-818, doi: 10.1002/grl.50196.
  - “Two-phase damage models of magma-fracturing”, Cai Z and Bercovici D, *Earth and Planetary Science Letters, 368 (2013) 1–8.*
  - “Rock deformation models and fluid leak-off in hydraulic fracturing”, Yarushina V, Bercovici D and Oristaglio M, *Geophysical Journal International,* accepted 2013 May 13, published online June 8, 2013
- Five manuscripts in preparation

Bibliography

- Papers presented at conferences
  - Integrated experimental and modeling studies of mineral carbonation, Workshop on Carbon Capture & Storage in Mafic and Ultramafic Rocks, January 8–10, 2011, Oman.
  - An experimental study of mineral sequestration of CO_2 by mafic/ultramafic rocks, AGU 2011, San Francisco, Global Environmental Change Poster Session GC51A, December 5–9, 2011.
  - Integrated experimental and modeling studies of mineral carbonation, USGS Workshop on Carbon Sequestration in Unconventional Reservoirs, March 28–29, 2012.
  - Experimental study of the kinetics of CO_2-sequestration by olivines and Hawaiian picrites, 22nd V.M. Goldschmidt Conference, June 24–29, Montréal, Canada