Geofluids — Part IV

Introduction to Geochemical and Reactive Transport Modeling

Dr. Svetlana Kyas (extension of the lecture notes of Dr. Allan Leal)

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Lecturers' introduction

Dr. Svetlana Kyas, Post-Doctoral Associate in Geothermal Energy & Geofluids

Dr. Allan Leal, Senior Research Assistant in Geothermal Energy & Geofluids

Introduction

Introduction

Course introduction

Course goal

- By the end of this course, you should become familiar with the fundamentals of **geochemical and reactive transport modeling** that includes of the following concepts:
  - chemical equilibrium;
  - chemical kinetics; and
  - chemical transport.
- For **numerical simulations** of simple geochemical and reactive transport problems, we will use Python and Reaktoro (`reaktoro.org`, computational framework that provides numerical methods for modeling chemically reactive processes governed by either chemical equilibrium, chemical kinetics, etc).

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Computational exercises

- This course will include a **computational project** using Python, Jupyter Notebook, and possibly Git:
  - The project **is graded** and helpful if you want to get the experience and improve you final grade. But **not necessary**. Possible forms of the project:
    (I) learning basics of geochemical simulation on one example (dissolving calcite in CO_2-rich brine) in Python,
    (II) learning Reaktoro (Python-based framework to model geochemical reactions) via doing hands-on Jupyter notebook exercises (on variety of problems), or
    (III) learning Reaktoro via Jupyter notebooks and by trying to model and program realistic application example (try out a new interesting application).
- Other computational tasks will be given throughout the lectures as **exercises, code-listings, and tutorials** (using Python scripts or Jupyter Notebooks).
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Poll on the you background and preferences

http://etc.ch/M2Rp

or

Tips for learning

- It is sufficient to learn the **basics of the Python 3** using

  `https://www.programiz.com/python-programming/tutorial`

- **Git** intro

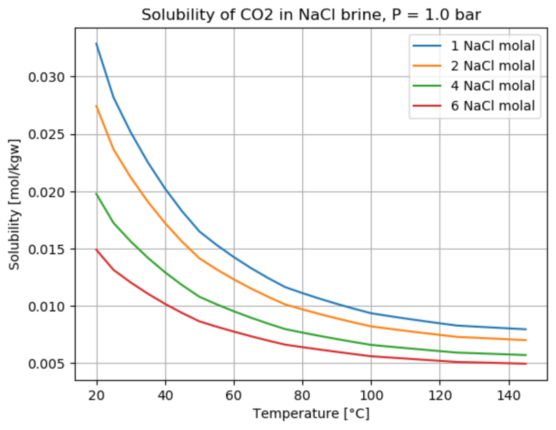
  `https://youtu.be/hwP7WQkmECE`

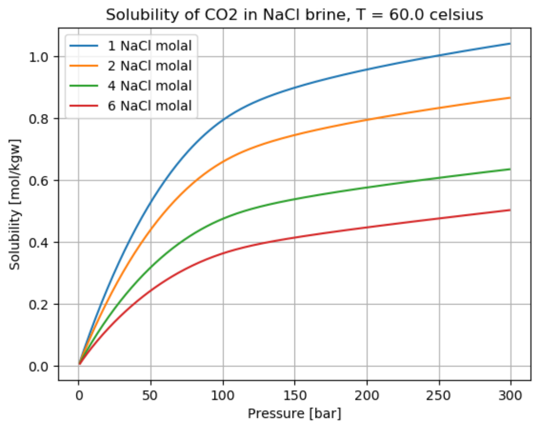
- Consider installing Python 3 using **Anaconda** using

  `https://www.anaconda.com/distribution/`

- Instruction of **installing Reaktoro** are also given using Anaconda are given in videos *Intro words*, *Installation on Windows / IoS*, and *Reaktoro Jyputer Notebook Installation* with explanation on Reaktoro installation and Jupyter Notebook tutorials execution are available *here*.
- Questions are always welcome via my email `svetlana.kyas@erdw.ethz.ch`.

Example of geochemical calculations, $CO_2(g)$ solubility in the NaCl-brine





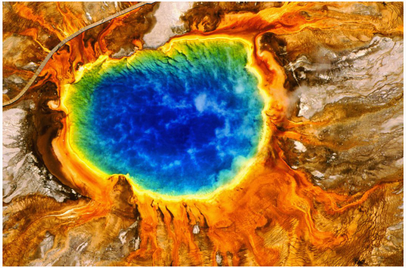
Note: See *Reaktoro v2.0 example* with the *Jupyter notebook*.

Introduction

A brief overview of geochemical modeling and its applications

What is geochemical modeling?

Geochemical modeling is the use of computers to simulate **chemical reactions** occurring in geologic systems, either **near the Earth's surface** or **deep in its interior**.



Geochemical reaction calculations for thermal springs for different conditions (Grand Prismatic, Midway Geyser Basin, Yellowstone, Wyoming, USA).

Geochemical reaction calculations for molten rocks as the magma flows from the Earth's mantle upwards.

Geochemical modeling applications, Scaling prediction in wells

Scale formation in a well as a result of geochemical reactions leading to mineral precipitation.

- Fluids coming from a reservoir experiences **temperature/pressure changes along the wells**.
- The decrease in temperature and/or pressure can lead to chemical reactions promoting precipitation of minerals and thus **scale formation** along the well.
- Geochemical modeling can be used to **predict**, **understand**, and **assist** on the remediation of scale formation.

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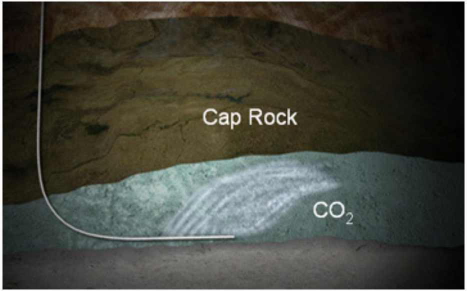
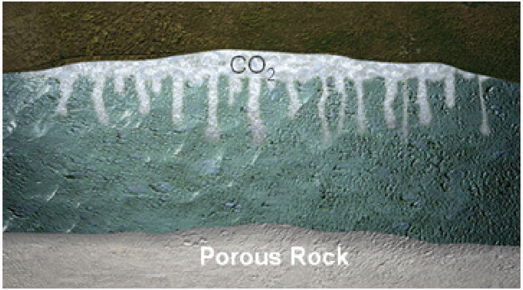
Geochemical modeling applications, CO_2 storage in geologic formations





Once CO_2 is injected in a deep saline aquifer, it starts to **dissolve into the resident brine**. Geochemical calculations can be used to calculate how much CO_2 dissolves and how much CO_2 continues mobile as gas or supercritical fluid.

Brine with dissolved CO_2 becomes acidic. It can then more easily **react with rock minerals**. This change rock properties, such as **porosity** and **permeability**. Geochemical calculations can tell **how much rock minerals dissolve**.

Geochemical modeling applications, Water analysis

Given the following water analysis, with the concentration of many chemical elements and pH, **find the concentrations of all aqueous species in the water**:

PARAMETER	UNITS	RESULTS
Conductivity	uS/cm	442
PH	-	7.5
Nitrate	mg N03/L	17
Sulphate	mg S04/L	<5
Chloride	mg Cl/L	14
Sodium	mg Na/L	7
Potassium	mg K/L	0.3
Calcium	mg Ca/L	92
Iron	mg Fe/L	<0.02
Copper	mg Cu/L	<0.01
Zinc	mg Zn/L	<0.01

Water composition as a result of a water analysis.

evian

Natural Spring Water

Country	France
Source	Évian-les-Bains
Type	still
pH	7.2
Calcium (Ca)	80
Chloride (Cl^-)	6.8
Bicarbonate (HCO_3)	350
Magnesium (Mg)	26
Nitrate (NO_3)	3.7
Potassium (K)	1
Silica (SiO_2)	15
Sodium (Na)	6.5
Sulfates (SO_4)	12.6
Website	http://www.evian.com

All values in milligrams per liter (mg/l)

See Jupyter notebook tutorial *Analysis of the Evian water*.

Geochemical modeling applications: Water analysis

Selected aqueous species that could exist in that water sample:

Cl-(aq)	CuO(aq)	H2(aq)	HNO2(aq)	KSO4-(aq)	OH-(aq)	SO3--(aq)
ClO-(aq)	CuO2--(aq)	H2N2O2(aq)	HNO3(aq)	N2(aq)	S2--(aq)	SO4--(aq)
ClO2-(aq)	CuOH+(aq)	H2O(aq)	HO2-(aq)	N2H5+(aq)	S2O3--(aq)	Zn++(aq)
ClO3-(aq)	Fe++(aq)	H2O2(aq)	HS-(aq)	N2H6++(aq)	S2O4--(aq)	ZnCl+(aq)
ClO4-(aq)	Fe+++(aq)	H2S(aq)	HS2O3-(aq)	N2O2--(aq)	S2O5--(aq)	ZnCl2(aq)
Cu+(aq)	FeCl+(aq)	H2S2O3(aq)	HS2O4-(aq)	NH3(aq)	S2O6--(aq)	ZnCl3-(aq)
Cu++(aq)	FeCl++(aq)	H2S2O4(aq)	HSO3-(aq)	NH4+(aq)	S2O8--(aq)	ZnO(aq)
CuCl(aq)	FeCl2(aq)	HCl(aq)	HSO4-(aq)	NO2-(aq)	S3--(aq)	ZnO2--(aq)
CuCl+(aq)	FeO(aq)	HClO(aq)	HSO5-(aq)	NO3-(aq)	S3O6--(aq)	ZnOH+(aq)
CuCl2(aq)	FeO+(aq)	HClO2(aq)	HZnO2-(aq)	Na+(aq)	S4--(aq)	
CuCl2-(aq)	FeO2-(aq)	HCuO2-(aq)	K+(aq)	NaCl(aq)	S4O6--(aq)	
CuCl3-(aq)	FeOH+(aq)	HFeO2(aq)	KCl(aq)	NaOH(aq)	S5--(aq)	
CuCl3--(aq)	FeOH++(aq)	HFeO2-(aq)	KHSO4(aq)	NaSO4-(aq)	S5O6--(aq)	
CuCl4--(aq)	H+(aq)	HN2O2-(aq)	KOH(aq)	O2(aq)	SO2(aq)	

Questions we want to answer:

- What are the **amounts of these species**?
- How **saturated** is the water **with respect to several minerals**?

  Note: *saturation* is the tendency of the solution to dissolve/precipitate a mineral.

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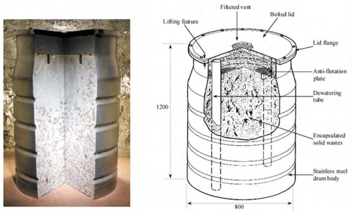
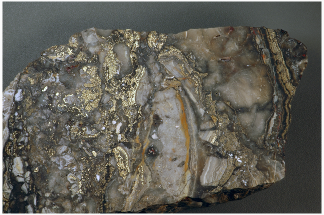
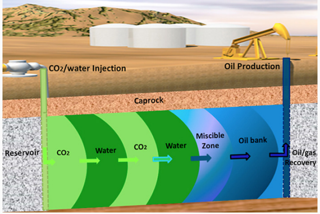
Other applications for geochemical modeling

- Geochemical reaction calculations can be used for a wide range of **industrial and environmental applications**:
  - nuclear waste management to ensure radionuclides remain properly stored for thousands/millions of years;
  - ore-forming processes;
  - geochemical reactions in geothermal and hydrothermal systems;
  - enhanced oil and gas recovery (prediction of gas and mineral solubility at the wide range of temperatures and pressures);
  - transport of reactive solution in porous and fractured media.







Introduction

Chemical equilibrium and chemical kinetics for modeling geochemical systems

Chemical reaction behavior, Initial intuition

- Consider 1 kg of H_2O mixed with 1 mg of NaCl (halite).
- Chemical reactions that occur among the species in the solution and the halite are as follows:

$$NaCl(halite, s) \rightleftharpoons Na^+ + Cl^-$$
$$Na^+ + Cl^- \rightleftharpoons NaCl(aq)$$
$$H_2O \rightleftharpoons H^+ + OH^-$$

- Detailed steps:
  - **pure water** solution contains species: H_2O, H^+, OH^-, $O_2(aq)$, $H_2(aq)$
  - **scale of the species** in water solution: 55.508 mol of H_2O, 1e-7 mol of H^+, 1e-7 mol of OH^- (to make sure the charge balance), 1e-31 mol of $O_2(aq)$, 1e-31 mol of $H_2(aq)$
  - after **mixing** NaCl(s) we have in addition: Na^+, Cl^-, NaCl(aq), HCl(aq), NaOH(aq)
  - **new ions** H^+ and Cl^- produce $H^+ + Cl^- \rightleftharpoons HCl(aq)$
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Poll on chemical equilibrium and kinetics

Quiz: In a context of this example and kinetic/equilibrium simulations, make a guess on which statement is correct?

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Answer:

- The chemical processes of the time scale of 1 ms are governed by equilibrium.
- The chemical processes of the time scale of 1 min are governed by kinetics.

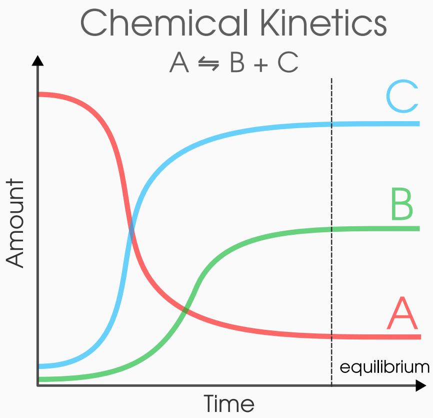
Chemical kinetics vs. Chemical equilibrium

Chemical Kinetics

- Focuses on **pathways of reactions** and **their rate**.
- Used to compute the amounts of the reacting species **over time**.

Chemical Equilibrium

- Focuses on the reactions with **no changes in the amount of reactants and products**.
- Used to directly compute the final composition of the species when the reactions are **in equilibrium**.



Chemical kinetics evolution of species A, B, and C over time.

Examples of chemical equilibrium reactions

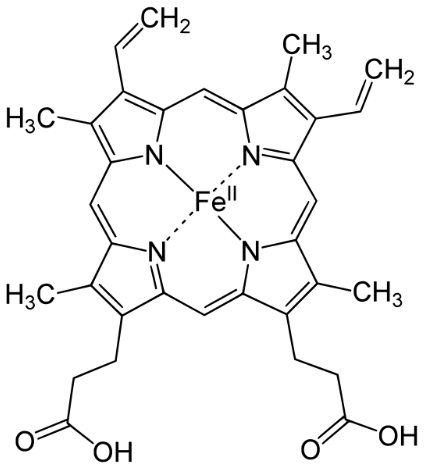
- **Bottle with soda drink**
  - $CO_2(g)$ dissolved in the liquid
  - $CO_2(g)$ is in the space between the liquid and the cap
  - CO_2 is constantly moving from the liquid to the gas phase, and back

$$CO_2(g) + H2O(l) \rightleftharpoons H_2CO_3(aq)$$

- **(Oxy)haemoglobin reactions in blood**
  - haemoglobin takes up oxygen and releases it

$$\text{haemoglobin}(aq) + 4O_2(g) \rightleftharpoons \text{haemoglobin}(O_2)_4(aq)$$

  - oxyhaemoglobin goes through the blood stream to cells



Hemoglobin structure.

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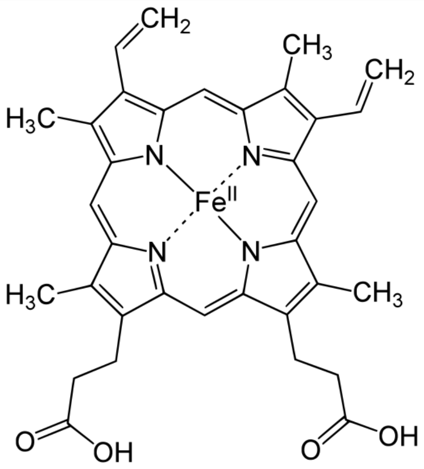

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Examples of chemical kinetics reactions

- **Corrosion**, a natural process that converts a refined metal into a more chemically stable form such as oxide, hydroxide, or sulfide:
  - galvanic corrosion
  - electrolytic corrosion
  - microbial corrosion
  - high temperature corrosion
- **Fluid catalytic cracking (FCC)**, a conversion process of petroleum crude oils into gasoline, olefinic gases, and other products. Used in petroleum refineries.

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Introduction

Practical observations on chemical equilibrium

Reaction classification

- **Irreversible** or **reversible**:
  - An **irreversible** reaction is one that occurs in only one direction and continues in this direction until at least one of the reactants is depleted.
  - A **reversible** reaction can occur in both directions (with forward and backward reaction reaction coefficients k_f and k_b, respectively):

$$\mathrm{a\,A} + \mathrm{b\,B} \underset{k_b}{\overset{k_f}{\rightleftharpoons}} \mathrm{c\,C} + \mathrm{d\,D}.$$

- **Homogeneous** or **heterogeneous**:
  - A **homogeneous** reaction involves a single phase, e.g.,

$$\text{Formation of ammonia} : N_2(g) + 3\,H_2(g) \rightleftharpoons 2\,NH_3(g)$$

$$\text{Oxidation of sulfur dioxide} : 2\,SO_2(g) + O_2(g) \rightleftharpoons 2\,SO_3(g)$$

  - A **heterogeneous** reaction involves more than one phase, e.g.,

$$\text{Carbonation} : Ca(OH)_2(s) + CO_2(g) \rightleftharpoons CaCO_3(s) + H_2O(l)$$

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$$\mathrm{a\,A + b\,B \underset{k_b}{\overset{k_f}{\rightleftharpoons}} c\,C + d\,D}.$$

- **Homogeneous** or **heterogeneous**:
  - A **homogeneous** reaction involves a single phase, e.g.,

$$\text{Formation of ammonia} : \mathrm{N_2(g) + 3\,H_2(g) \rightleftharpoons 2\,NH_3(g)}$$

$$\text{Oxidation of sulfur dioxide} : \mathrm{2\,SO_2(g) + O_2(g) \rightleftharpoons 2\,SO_3(g)}$$

  - A **heterogeneous** reaction involves more than one phase, e.g.,

$$\text{Carbonation} : \mathrm{Ca(OH)_2(s) + CO_2(g) \rightleftharpoons CaCO_3(s) + H_2O(l)}$$

Practical observations on chemical equilibrium

- Chemical reactions **alter the amounts of species over time**, where species can be distributed among one or more phases (minerals, gaseous or aqueous phases).
- Each of these reactions have **forward and backward rates**.
- Consider the reaction

$$\mathrm{A} + \mathrm{B} \underset{k_b}{\overset{k_f}{\rightleftharpoons}} \mathrm{C} + 2\,\mathrm{D},$$

- Rate of the reaction is measured in mol/s.
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- **forward rate** = **production rate** > 0,
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Quiz: What is **rate of production/consumption** of A, B, C and D (in mol/s), assuming the the forward and backward reaction rates are 1 mol/s?

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Answer:

- production rates are 1 mol/s for C, 2 mol/s for D;
- consumption rates are -1 mol/s for A, -1 mol/s for B.

Chemical equilibrium of species

Quiz: What happens when this **net rate** is **zero** in a context of reaction

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Answer:

- the amounts of each species in the system **no longer experience any change**, and
- they are in **chemical equilibrium**.

Example explaining the reaction net rate

Let us mix 1 kg of H_2O with NaCl (halite):

$$\begin{aligned} \mathrm{NaCl(halite, s)} &\rightleftharpoons \mathrm{Na^+ + Cl^-} \\ \mathrm{Na^+ + Cl^-} &\rightleftharpoons \mathrm{NaCl(aq)} \\ \mathrm{H_2O} &\rightleftharpoons \mathrm{H^+ + OH^-} \end{aligned}$$

Let us consider **two scenarios**:

- If we take **1 mg of NaCl**, eventually, all salt fully dissolves, so the net rate of production of Na^+ and Cl^- becomes zero.
- If we take **100 mg of NaCl**: eventually, water solution will be saturated with the salt, so Na^+ and Cl^- is precipitating NaCl with the similar rate as it is dissolving.

Note: See a Jupyter notebook *On mixing table salt with water*.

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- Consider the following **CO_2 dissolution/exsolution reaction**:

$$H_2O(aq) + CO_2(g) \rightleftharpoons HCO_3^-(aq) + H^+(aq)$$

- This **reaction is in equilibrium** when $CO_2(g)$ is **dissolving** (*from gas to solution*) and **exsolving** (*from solution to gas*) at the same rate.
- Alternatively, we can have the following **aqueous-gaseous reaction**:

$$CO_2(g) \rightleftharpoons CO_2(aq)$$

Note: see the tutorial *On opening bottle with soda* with Jupyter notebook *here*.

- **Good to know:** The **solubility of CO_2** (i.e., the maximum amount of CO_2 that the solution can dissolve at given temperature, pressure, and fluid composition conditions) can be calculated considering this reaction (and all others) in equilibrium.

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Introduction

Defining the chemical system in the geochemical modeling problem

Defining the chemical system for the modeling problem

- A **chemical system** is a **collection of phases** (one or more). Examples:
  - a chemical system with only an aqueous phase;
  - a chemical system with aqueous and gaseous phase ($CO_2(g)$);
  - a chemical system with aqueous, gaseous, and mineral phases.
- Each phase has one or more chemical species:
  - aqueous: $H_2O(aq)$, $H^+(aq)$, $OH^-(aq)$, $HCO_3^-(aq)$, $CO_3^{2-}(aq)$, $CO_2(aq)$, $Ca^{2+}(aq)$
  - gaseous: $H_2O(g)$, $CO_2(g)$, $O_2(g)$, $H_2S(g)$
  - calcite: $CaCO_3(s)$
  - solids: combination of several minerals, e.g., Granite: 30% of Calcite, 33% of Albite, 32% of K-Feldspar, 5% of Muscovite.
  - oil
  - biomass (to simulate life of bacterias)
- In geochemical modeling, suitable phases and their species need to be considered. They must be added either:
  - manually (naming each species separately, e.g., ['H2O(l)', 'H+', 'OH-', 'Na+', ...]) or
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Demonstration of chemical system definition i

```python
from reaktoro import *

# Define the SUPCRT database
db = SupcrtDatabase("supcrtbl")

# Define an aqueous solution
solution = AqueousPhase(speciate("H O Na Cl Ca C"))

# Define gaseous phase
gas = GaseousPhase("CO2(g)")

# Define mineral phase
minerals = MineralPhases("Halite Calcite Dolomite")

# Create the chemical system
system = ChemicalSystem(db, solution, gas, minerals)

```

Demonstration of chemical system definition ii

```python
# Inspect species phases and species
for phase in system.phases():
    print(phase.name())
    for species in phase.species():
        print(":: " + species.name())
```

Listing 1: Chemical system definition

See also:

- Reaktoro v2.0 Jupyter notebook tutorials on the Reaktoro website *Basics* or
- similar Jupyter notebook *Basics* with interactive version available via *MyBinder Reaktoro v2.0*.

Example of the chemical system when H_2O and CO_2 are involved

- Assume water (H_2O) and carbon dioxide (CO_2), are mixed at given T and P.
- To model the equilibrium state resulting from this process, the first step is to think about:
  - the possible phases of matter that could exist; and
  - the species in each phase.
- **Questions we are interested in**:
  - Is CO_2 fully dissolved, or is it still present as a gas (water is already fully saturated with it)?
  - What are the amounts of each species in the chemical state after equilibration?

- A simple (but reasonable) chemical system for this problem is:

Aqueous Phase	**Gaseous Phase**
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- Assume water (H_2O), carbon dioxide (CO_2), and sodium chloride (NaCl), are mixed at some given temperature T and pressure P.
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$OH^-(aq)$	$CO_3^{2-}(aq)$		
$Na^+(aq)$	NaCl(aq)		
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  - How does the salinity of the brine impact the solubility of halite in it?
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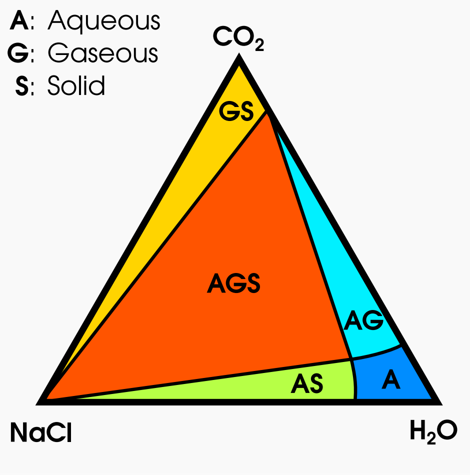
- In general, the **number of phases and species** should be **as large as possible** when *defining a chemical system*.
- However, the calculations get more expensive with increasing number of species and phases.
- **Important:** Not all phases considered in the calculation will actually exist in positive amounts. Their existence depends on the input conditions.
- The ternary phase diagram on the right shows conditions in which not all phases are **stable at equilibrium**.



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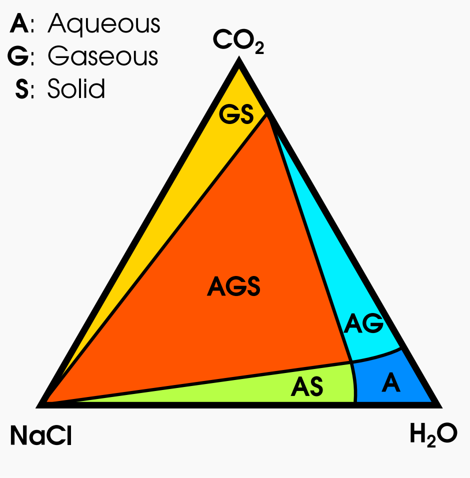

Ternary phase diagram.

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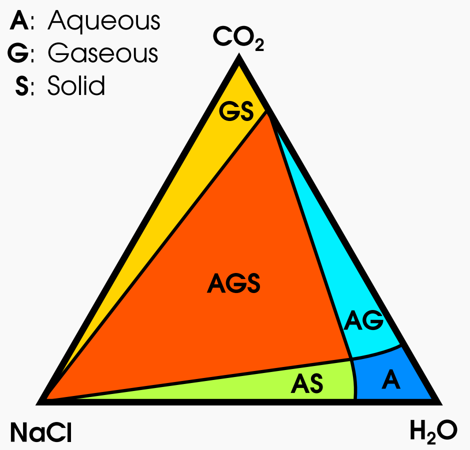
- In general, the **number of phases and species** should be **as large as possible** when *defining a chemical system*.
- However, the calculations get more expensive with increasing number of species and phases.
- **Important:** Not all phases considered in the calculation will actually exist in positive amounts. Their existence depends on the input conditions.
- The ternary phase diagram on the right shows conditions in which not all phases are **stable at equilibrium**.



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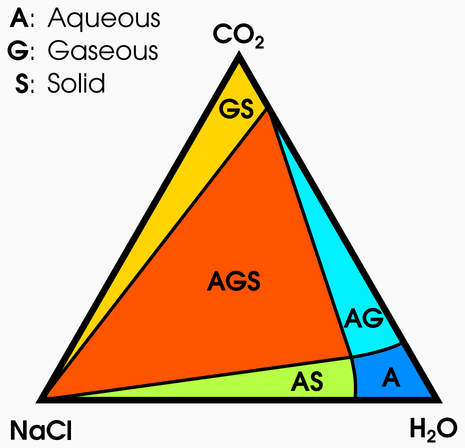

Ternary phase diagram.

Final considerations about defining the chemical system

- In most computer codes for modeling geochemical reactions, no manual selection of phases and species are needed.
- These can be determined **automatically** by searching in **thermodynamic databases** all possible species and phases that could exist for a given model input.
- Depending on the available database, you can model different things:
  - supcrt98.xml
  - supcrt98-organics.xml (includes organic species)
  - thermofun.json ($T = 200$ °C, critical temperatures and pressures of gases used in Peng-Robinson's EOS)
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References

- Interactive MyBinder Reaktoro v2: *link*
- Hands-on Jupyter notebooks Reaktoro v2: *link*
- Link with instruction no how to start working with Jupyter notebooks for Reaktoro v2: *link*
- Hands-on Jupyter notebooks Reaktoro v1: *link*
- Videos explaining some Jupyter notebooks with Reaktoro v1: *link*