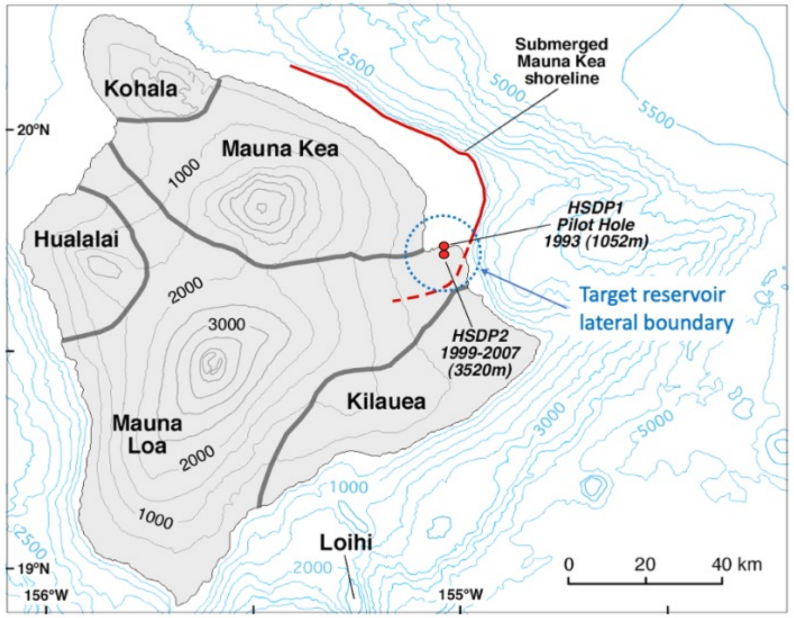
Subsurface Carbon Mineralization Resources in Hawai'i Basalt

Donald J. DePaolo
Lawrence Berkeley National Laboratory

Nicole Lautze (PI)
University of Hawaii

PI: Nicole Lautze, U. Hawaii

Other personnel:
Don Thomas – U. Hawaii
Don DePaolo – LBNL/UC Berkeley
Bhavna Arora – LBNL
Nori Nakata - LBNL
Pramod Bhuvankar - LBNL



Collaborators:
Ziqiu Xue – RITE, Japan
Saeko Mito – RITE, Japan

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Climeworks (S)

Outline

Subsurface Carbon mineralization resources in Hawaii Basalt (current project starting 2023)

1. Downhole logging, sampling and pressure testing using the HSDP 3500m deep well
2. Geophysical imaging of subsurface reservoirs
3. Geochemical characterization of formation fluids
4. Reactive transport modeling of trapping and mineralization
5. Hydrogeologic modeling of ambient circulation and impacts of injection
6. Laboratory experiments on glassy basaltic clastic rocks from the section

Large-scale carbon storage potential of saline volcanic basins (2019 – 2023)

1. Geochemical characterization of archived fluid samples and implications for mineralization
2. Hydrologic modeling of thermohaline circulation and subsurface temperatures
3. Basin scale flow and reactive transport modeling of CO_2 injection in saline basalt formations to evaluate structural and solution trapping and mineralization
4. Laboratory experiments to constrain kinetics of mineralization
5. Development of TOUGH+ module for CO_2 hydrate trapping
6. Inversion of water level and tidal data for deep permeability

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Initial assessment is summarized in 2021 IJGGC paper

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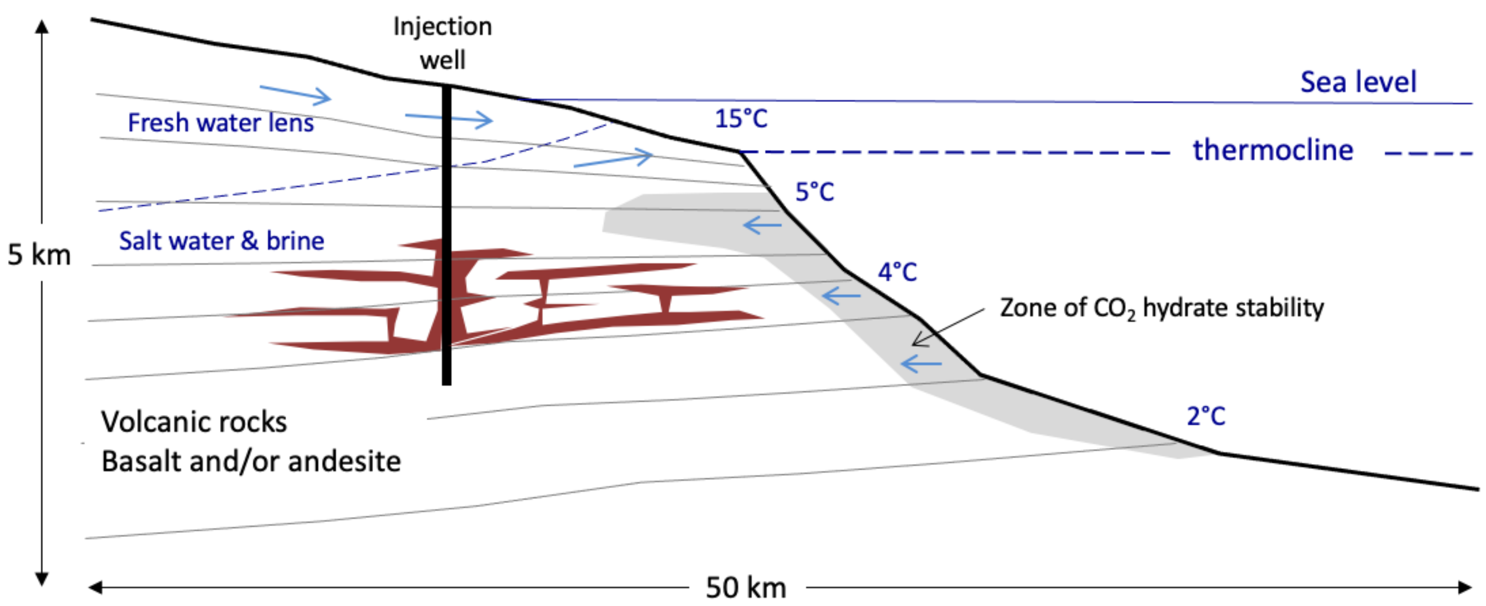
Opportunities for large-scale CO_2 disposal in coastal marine volcanic basins based on the geology of northeast Hawaii

Donald J. DePaolo[a,*], Donald M. Thomas[c], John N. Christensen[a], Shuo Zhang[d], Franklin M. Orr[b], Kate Maher[b], Sally M. Benson[b], Nicole Lautze[c], Ziqiu Xue[e], Saeko Mito[e]

[a] *Energy Geosciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA*
[b] *School of Earth Energy and Environmental Science, Stanford University, Stanford, CA, 94305, USA*
[c] *Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI, 96822, USA*
[d] *Department of Hydraulic Engineering, Tsinghua University, Beijing, 100084, China*
[e] *Research Institute of Innovative Technology for the Earth (RITE), Kizugawadai 9-2, Kizugawa-shi, Kyoto 619-0292, Japan*

Concept for large scale CO_2 disposal

The concept is based on the subsurface geology and hydrology of the NE portion of the island of Hawaii, for which there is direct information available from previous drilling and coring



Schematic concept of near-shore geological and thermal structure of large oceanic volcanic edifices like those of Hawaii

"Deep saline volcanic basins" (basalt and andesite) may be able to utilize multiple trapping mechanisms:

(1) Lower temperatures make CO_2 less buoyant

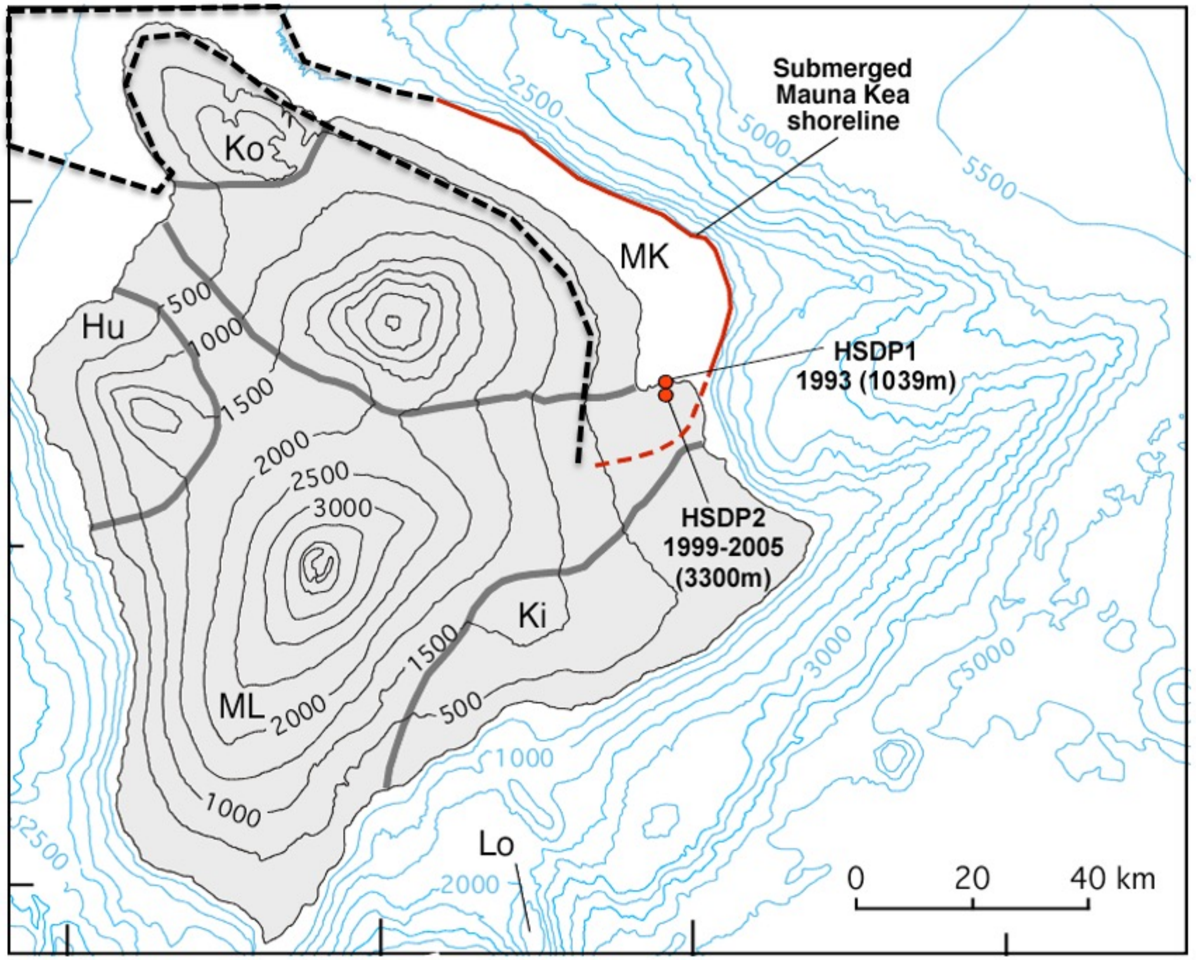
(2) Large formation thicknesses (>3 km) and heterogeneity provide structural trapping

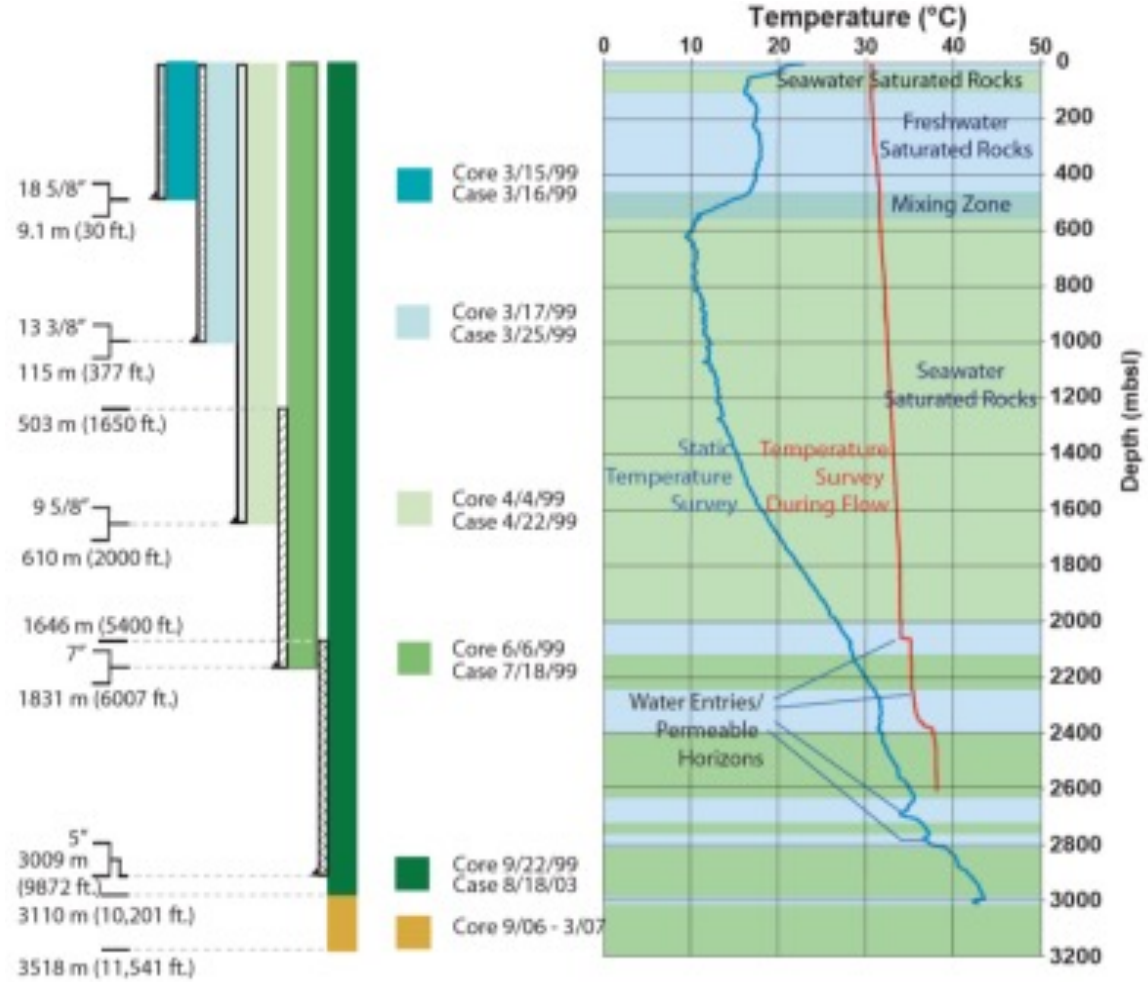
(3) Pure CO_2 could potentially be injected from onshore wells

(4) Dissolution, capillary, and mineral trapping, as well as CO_2-hydrate formation, could contribute to immobilizing CO_2

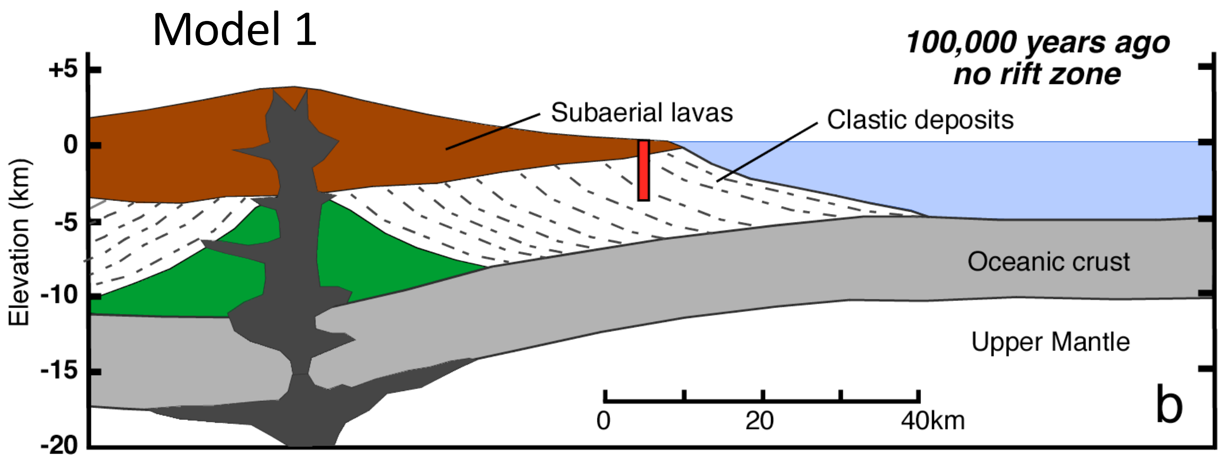
Field test site – Northeast Hawaii

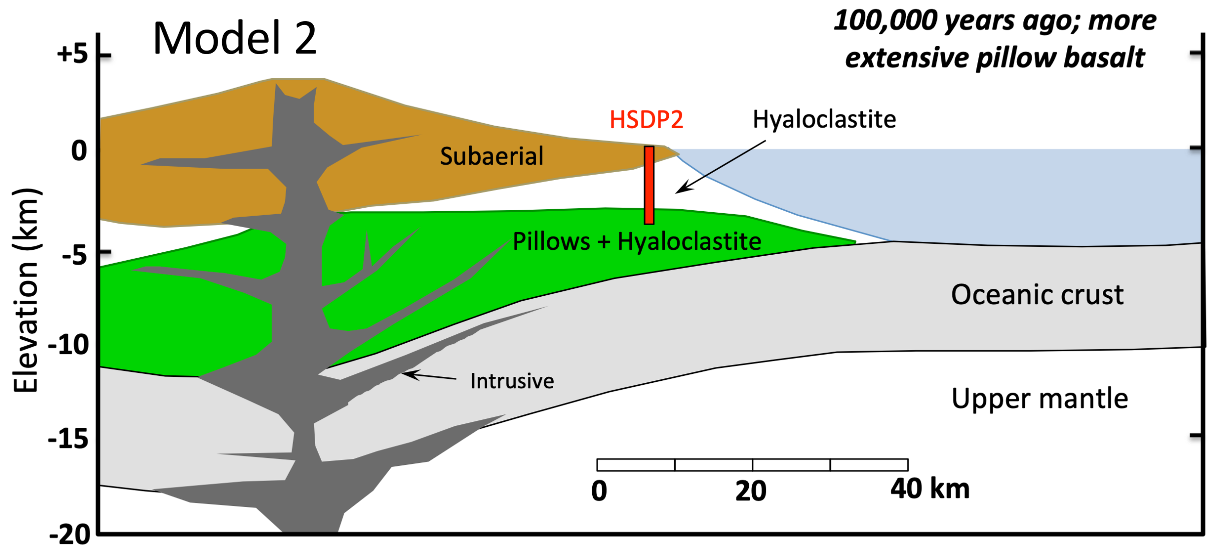
Existing 3540' deep well drilled and cored as part of an NSF project in 1999 – 2005 (HSDP)

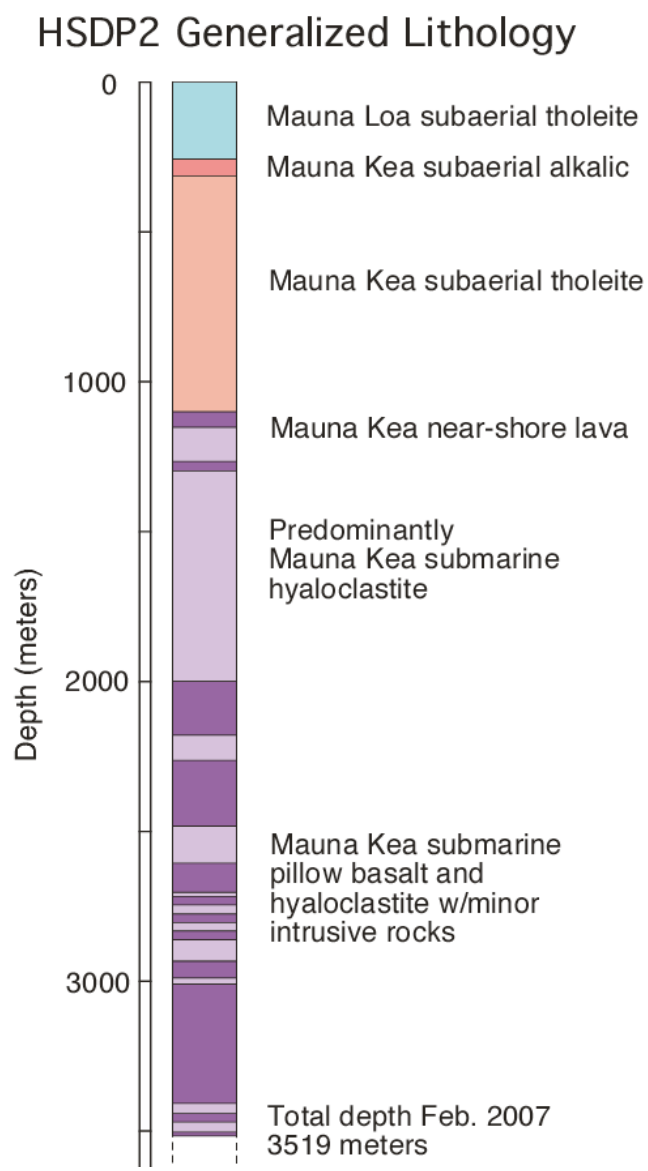


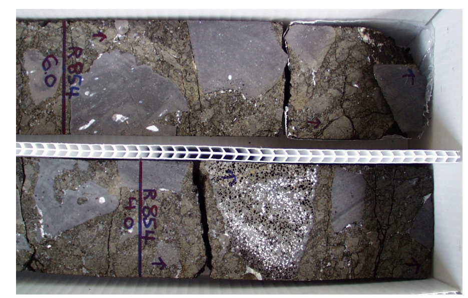


Growth of Hawaiian volcanoes is sufficiently systematic that facies models have been developed



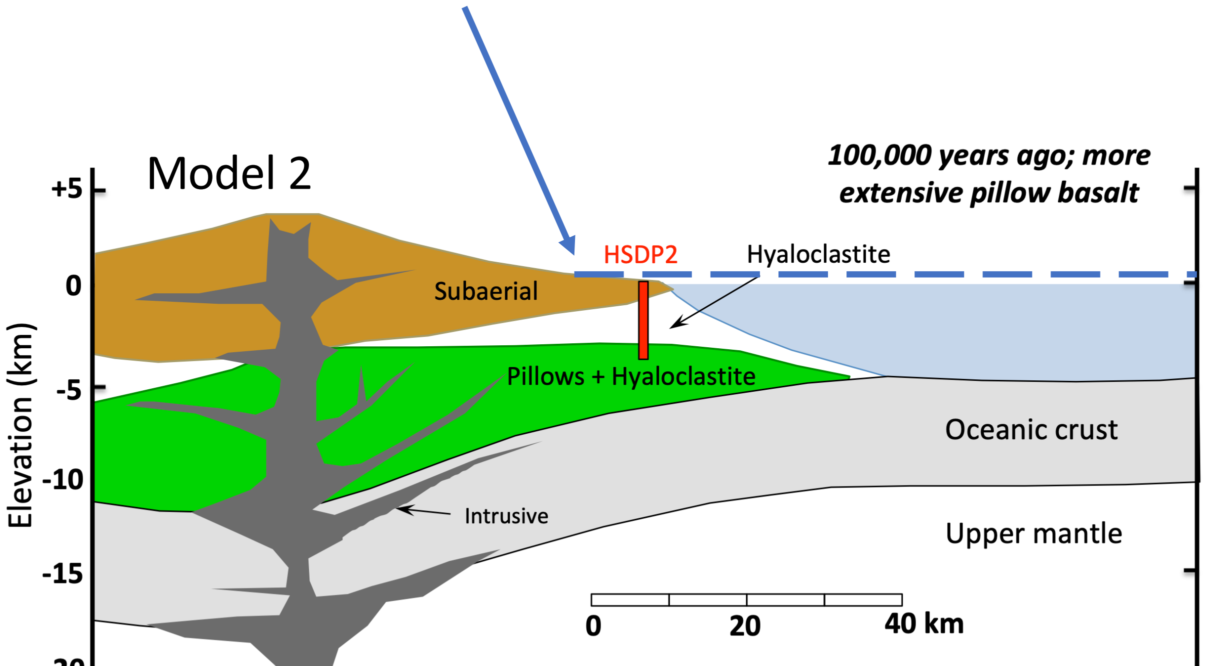


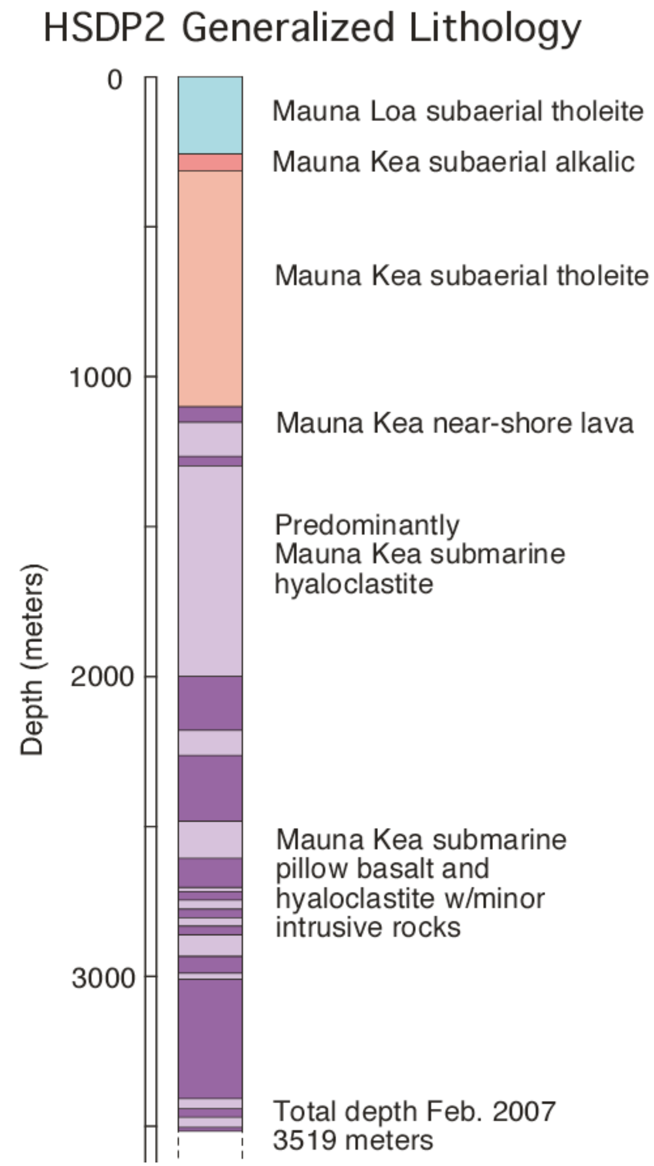


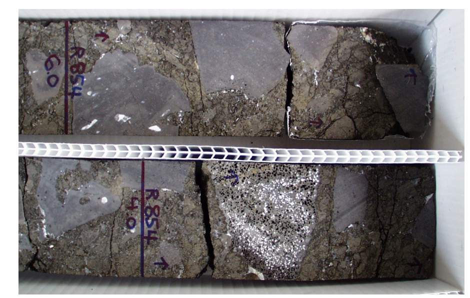


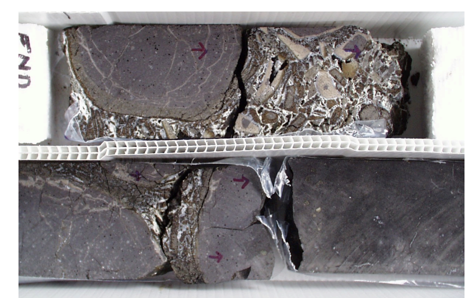
Growth of Hawaiian volcanoes is sufficiently systematic that facies models have been developed

After eruption ceases the volcanoes continue to subside and the shoreline moves upslope toward the summit

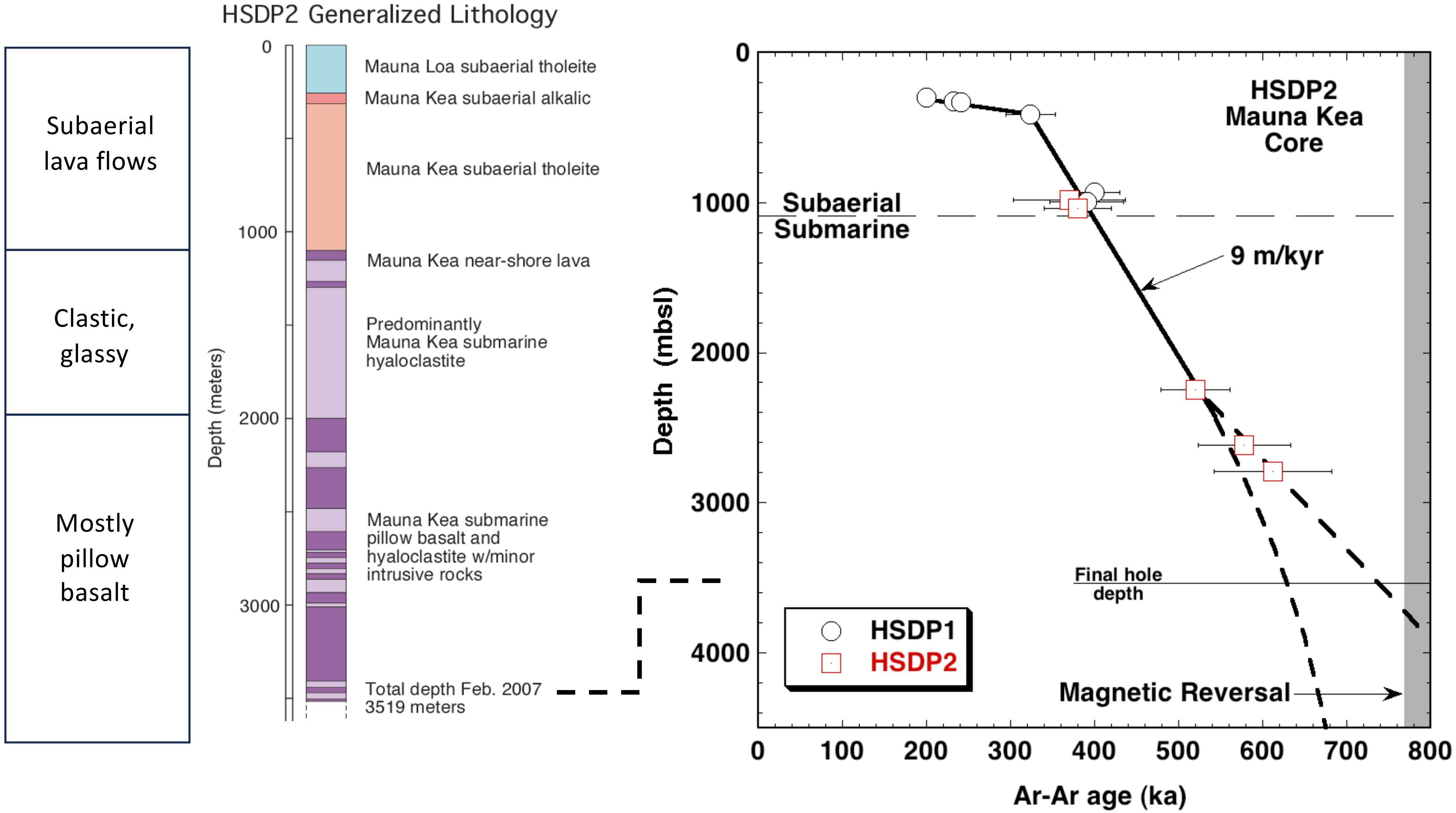








Basaltic rocks are geologically young (< 1 Ma) and reactive, enhancing mineralization potential



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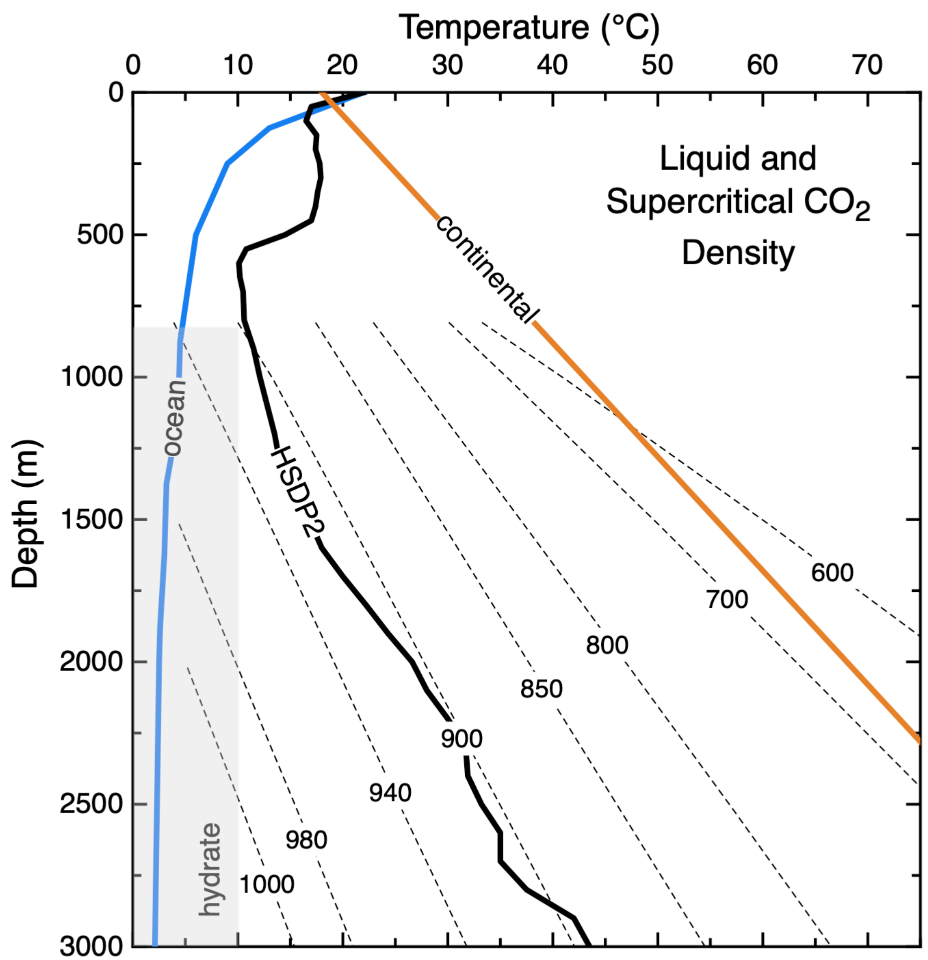
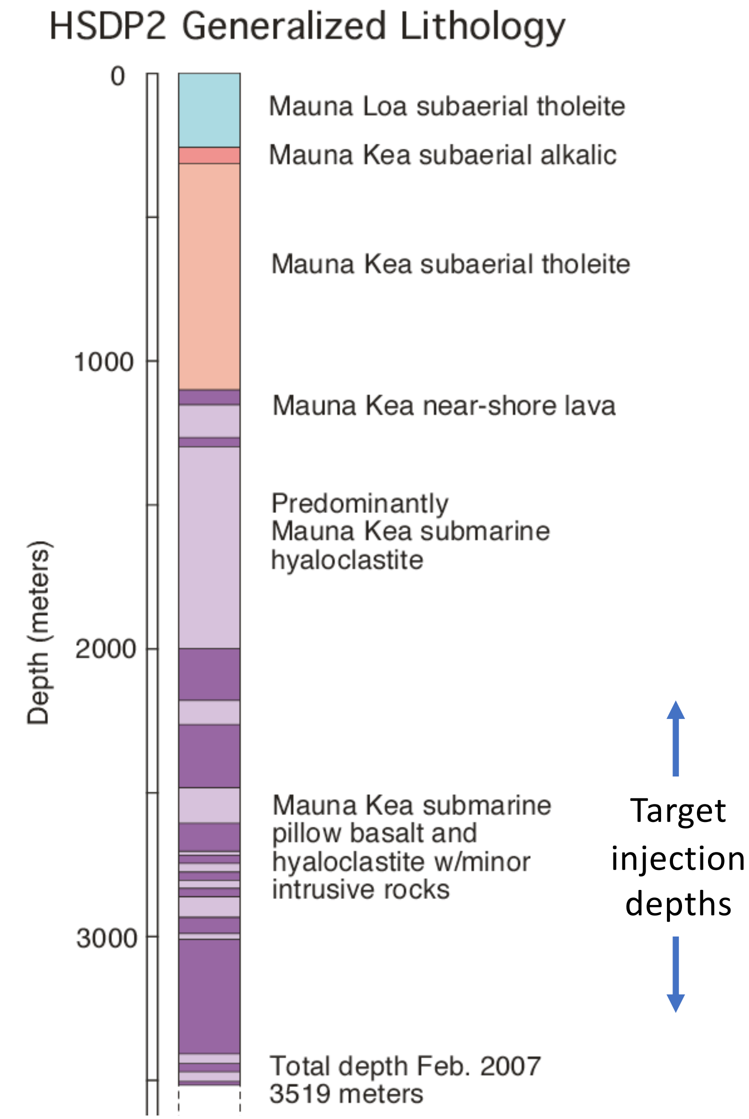
Temperature and hydrologic properties under Hilo





≥ 10 D	High-k Fresh water
≥ 10 D	High-k Seawater
< 1 mD	
Zones > 1 D	Intercalated Low-k and high-k layers Brackish to hypersaline
Zones > 50 mD	

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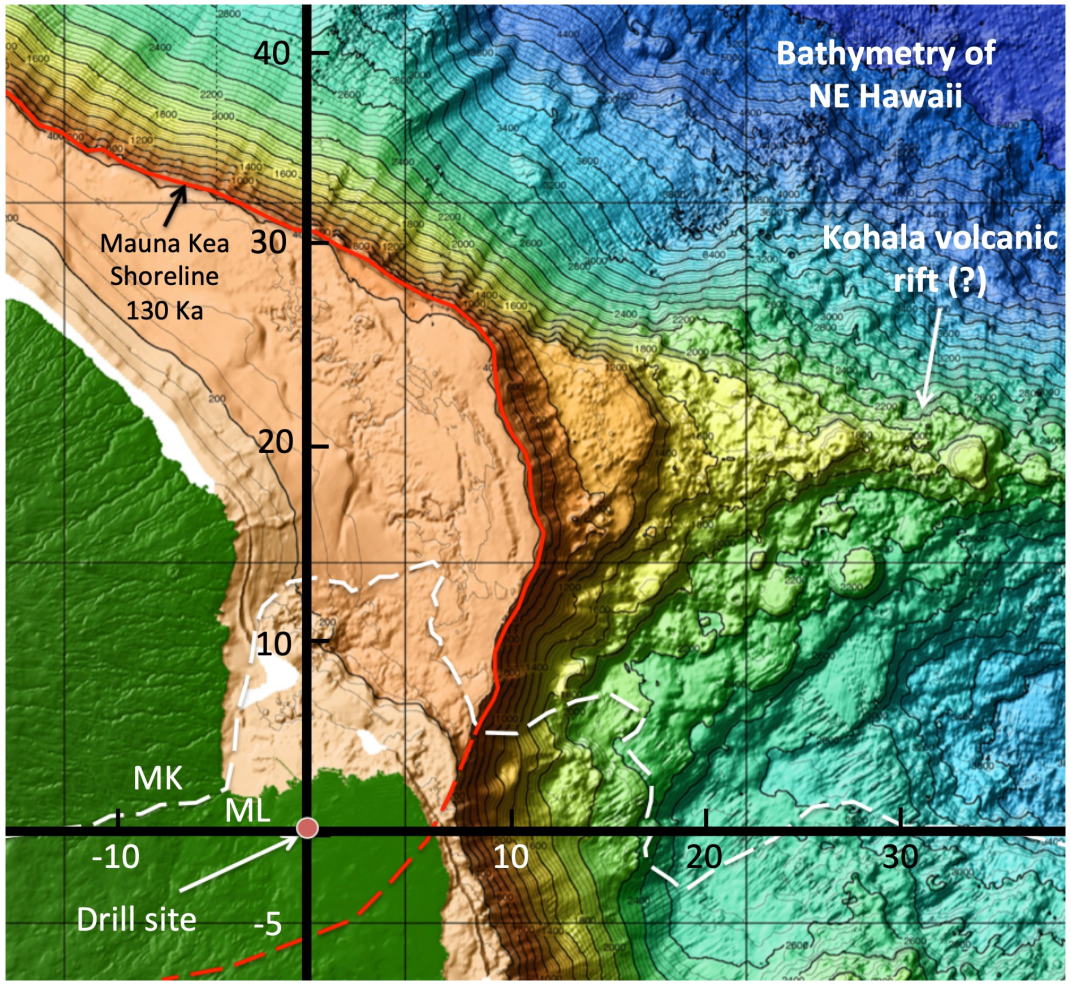
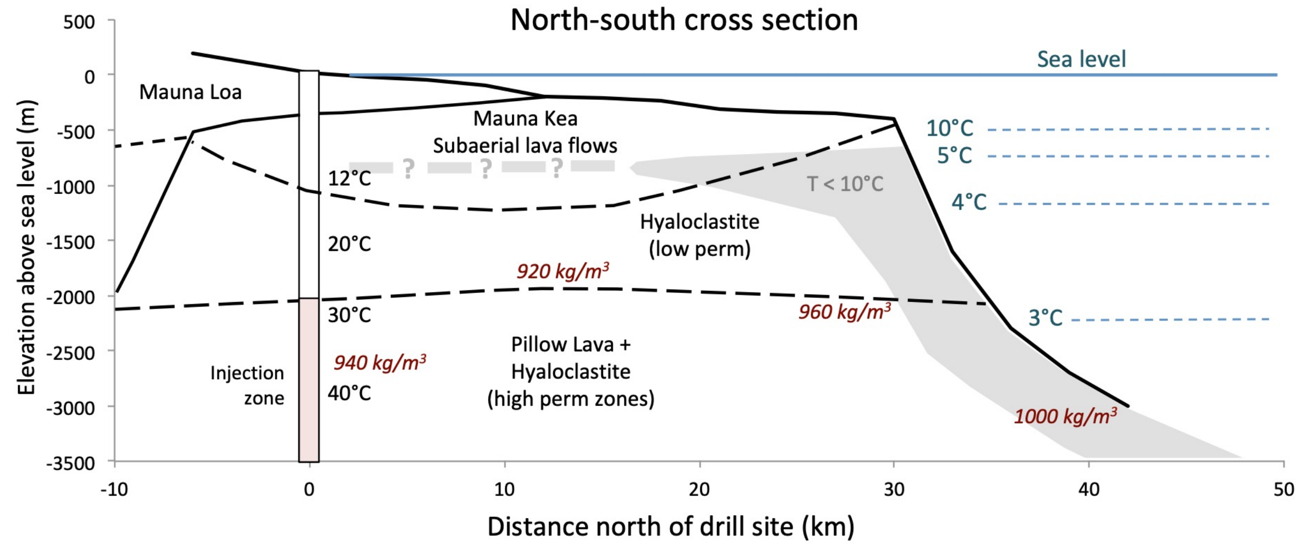
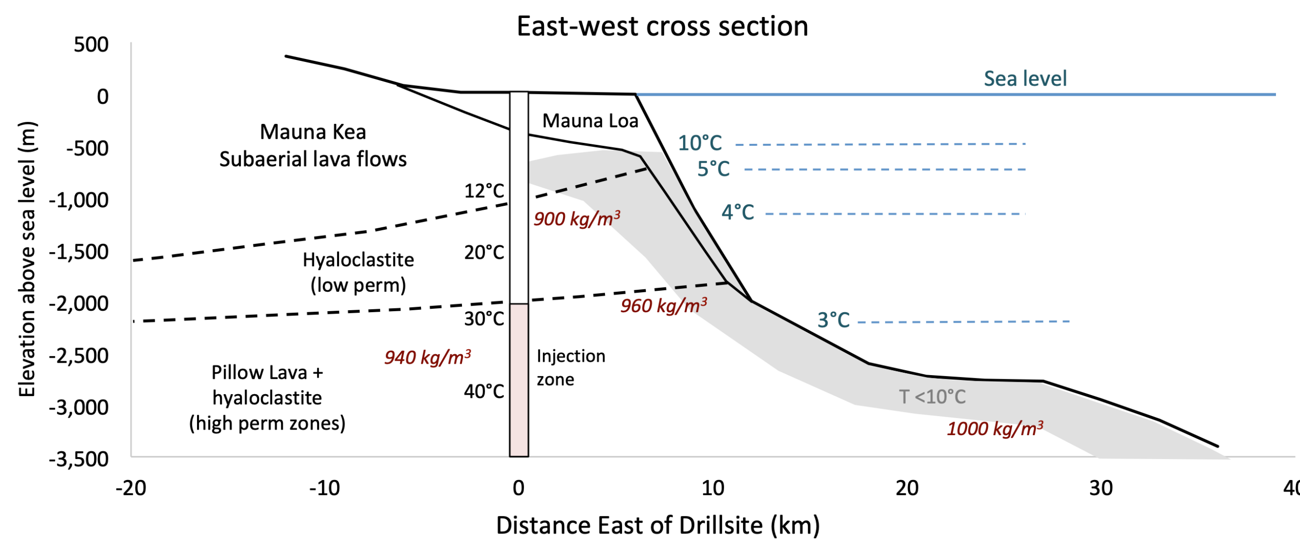
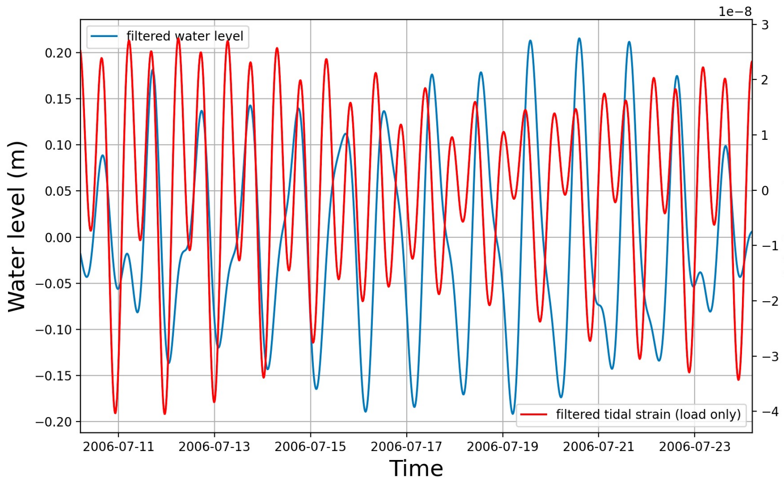
Subsurface site model based on drillcore and volcano growth models

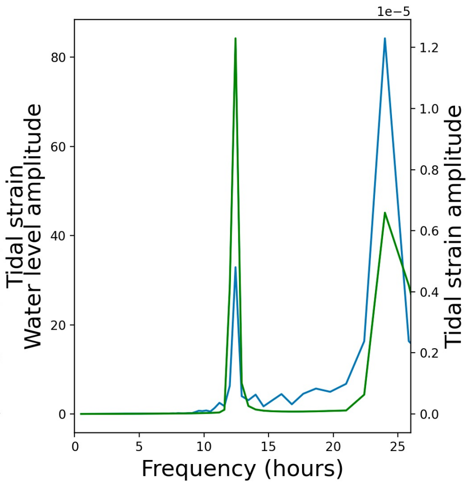






Deep Permeability Inferred from Tidal Time Series Analysis

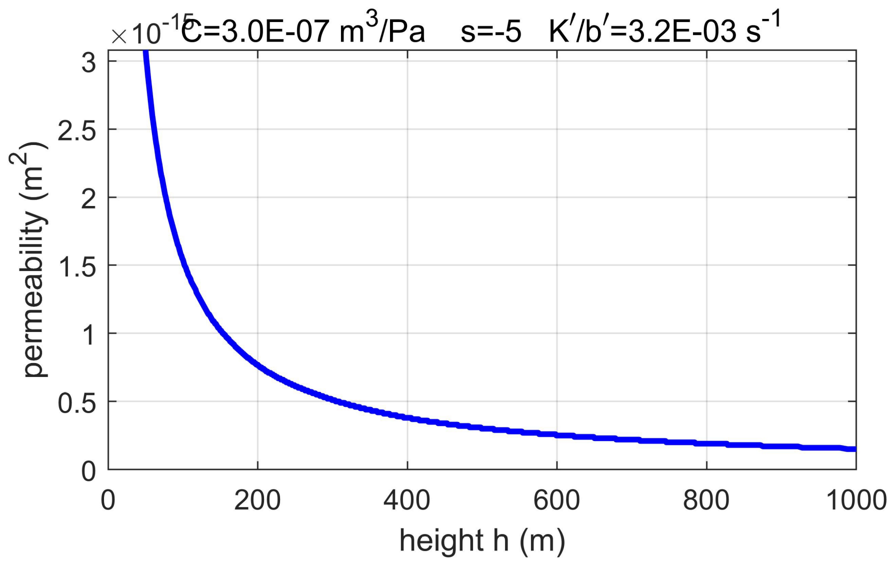


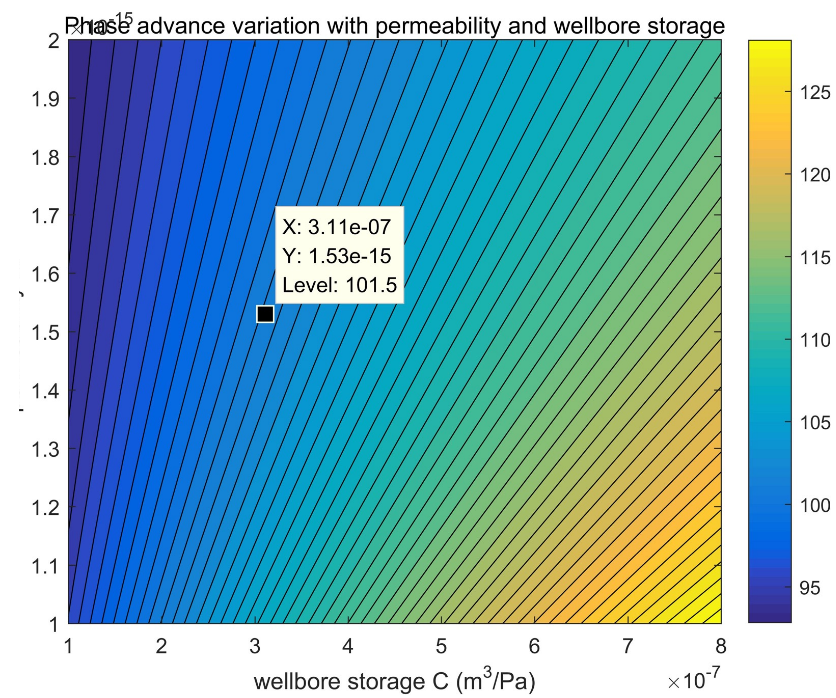


Water level – tidal forcing analysis suggests bulk permeability at depth below the well casing at 3000m is a few millidarcy

But allows for thinner (3-meter) zones of much higher permeabilty

Analysis by
Xunfeng Lu,
Kozo Sato, and
Roland Horne
Stanford University





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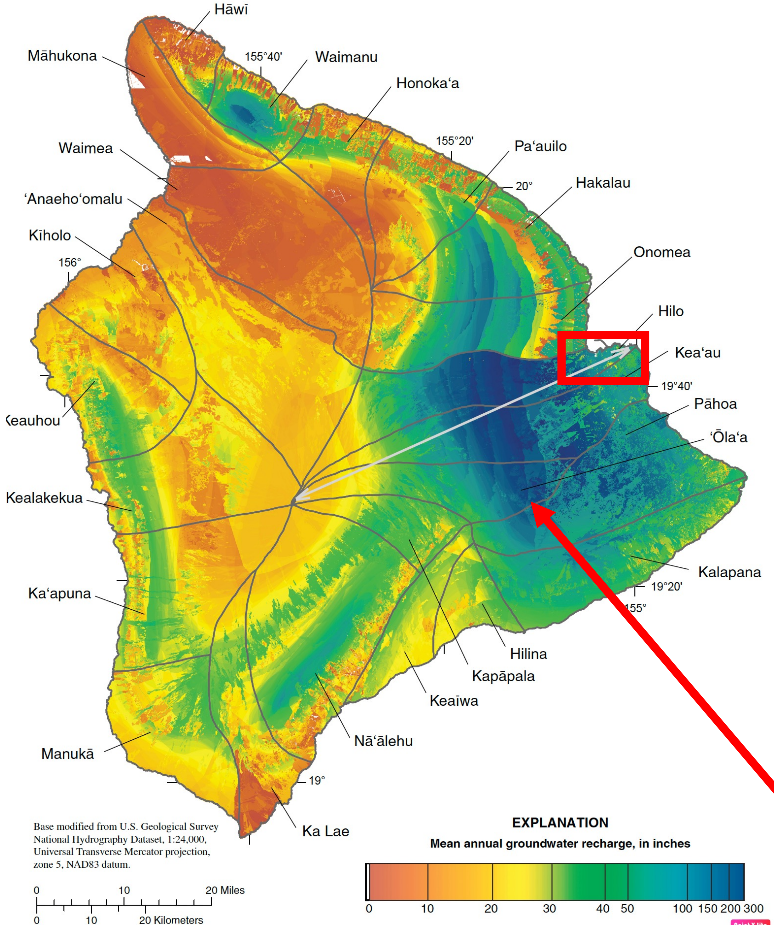
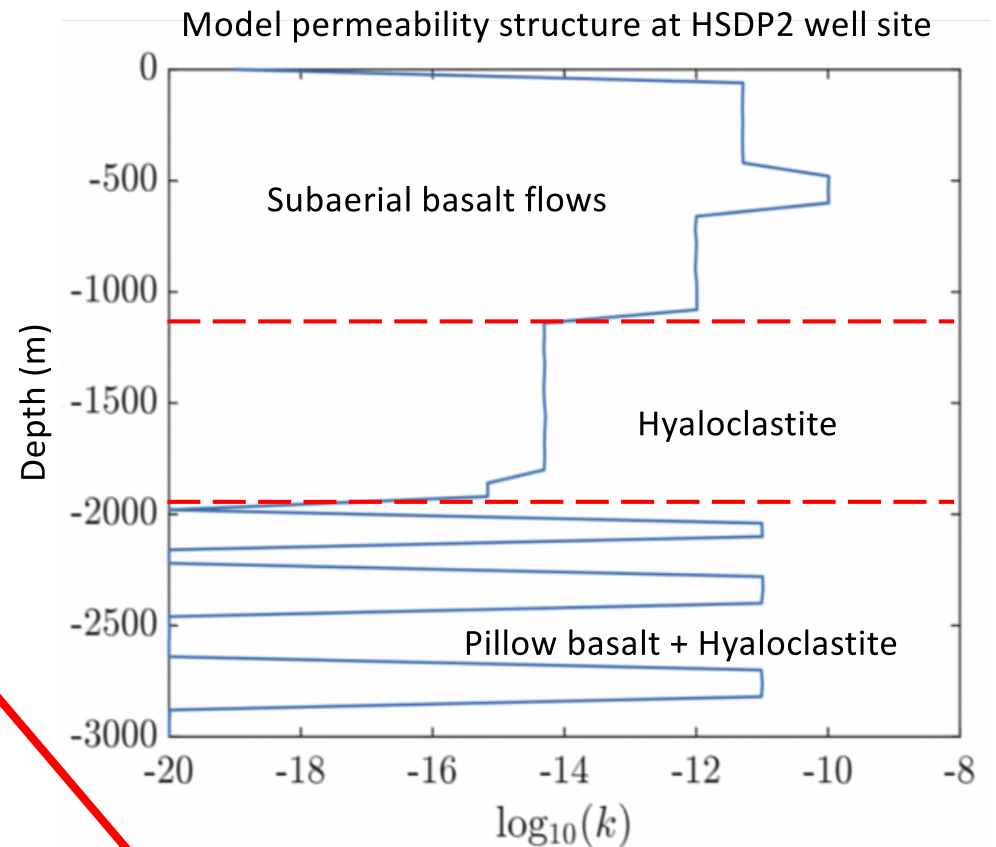
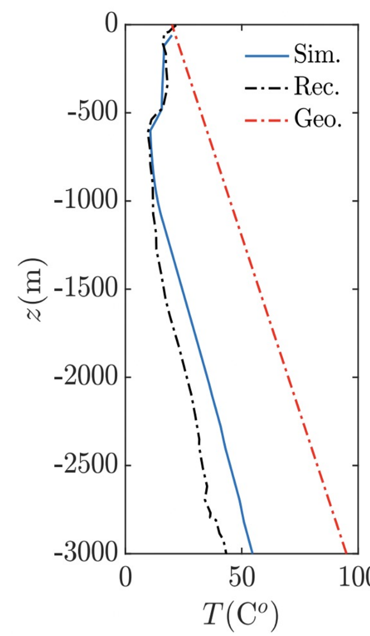
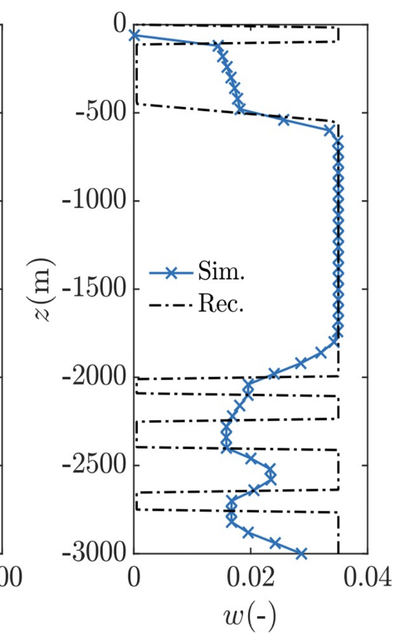
Thermohaline convection models are consistent with other inferences from water entries and tidal analysis

Abdullah Cihan and Pramod Bhuvankar (LBNL)









Recharge flux > 150 inches/year

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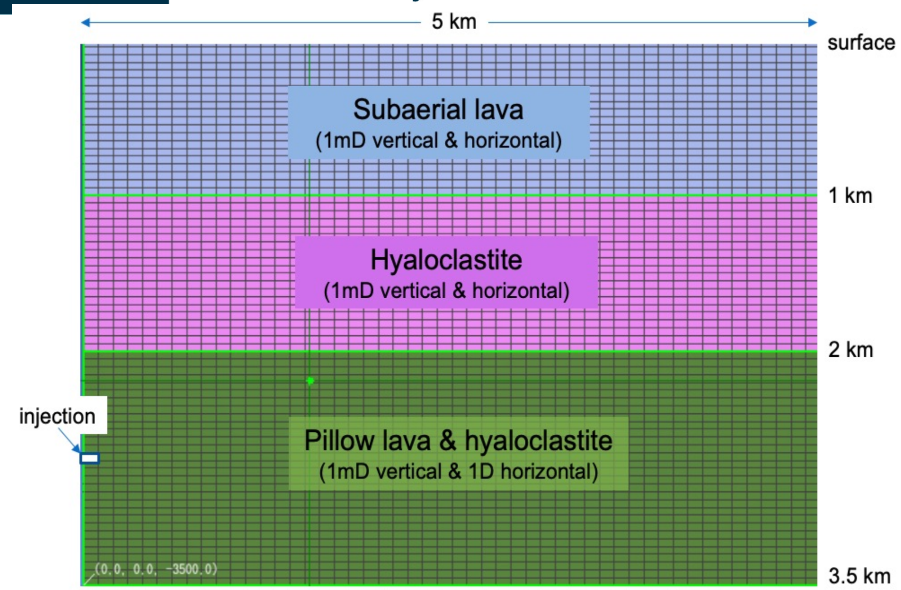
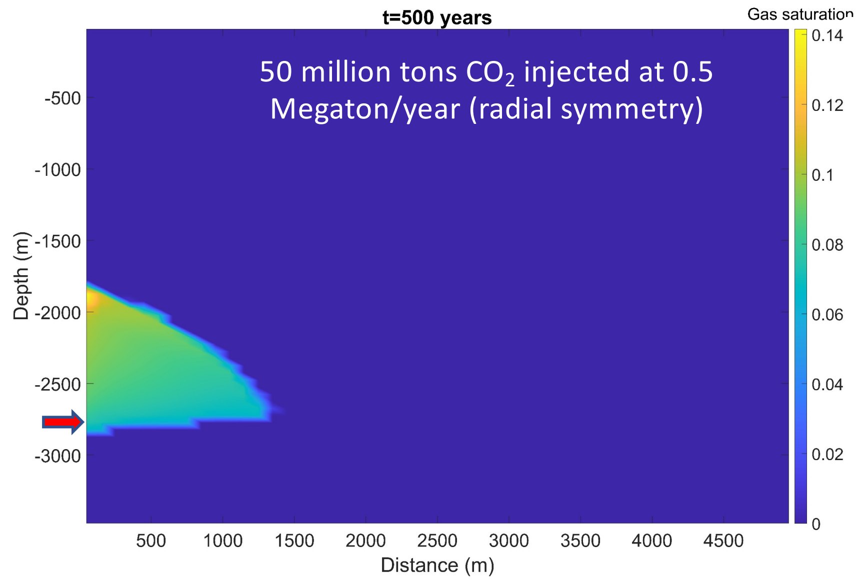
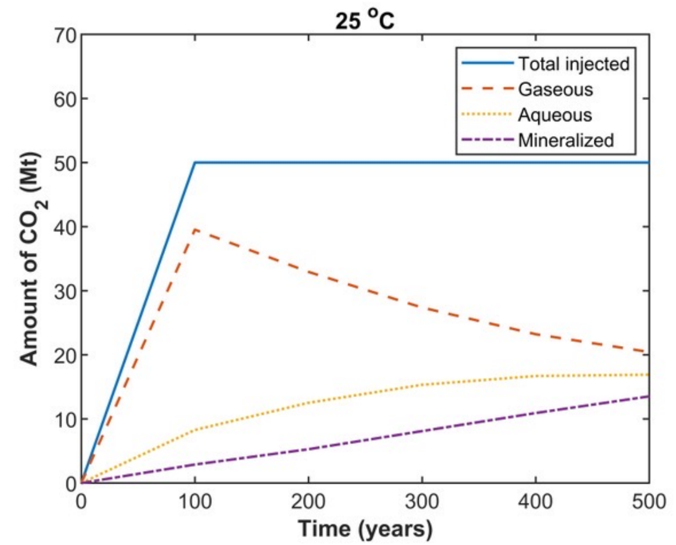
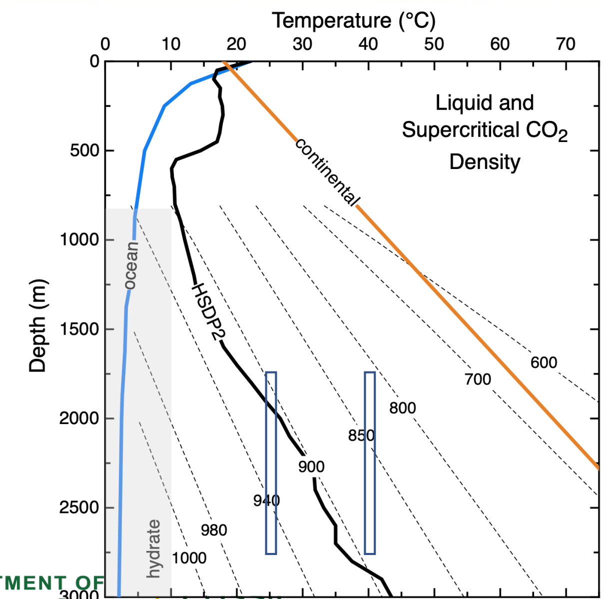
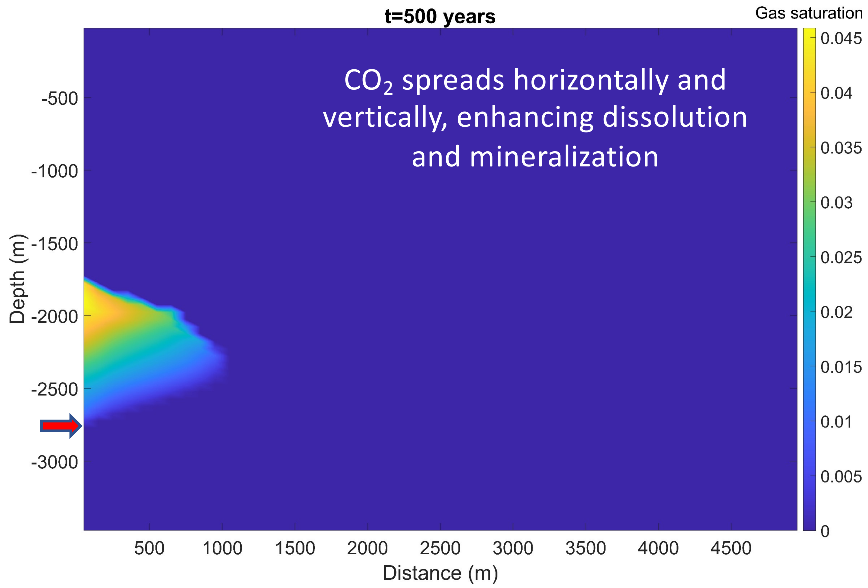
Preliminary injection models using TOUGHREACT

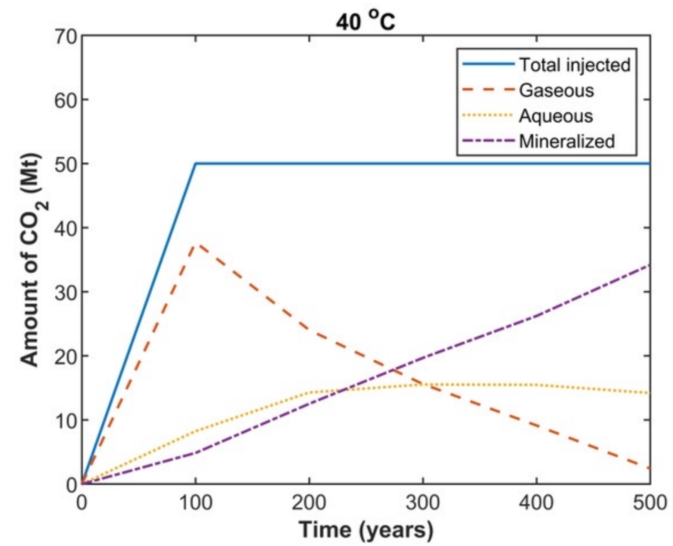


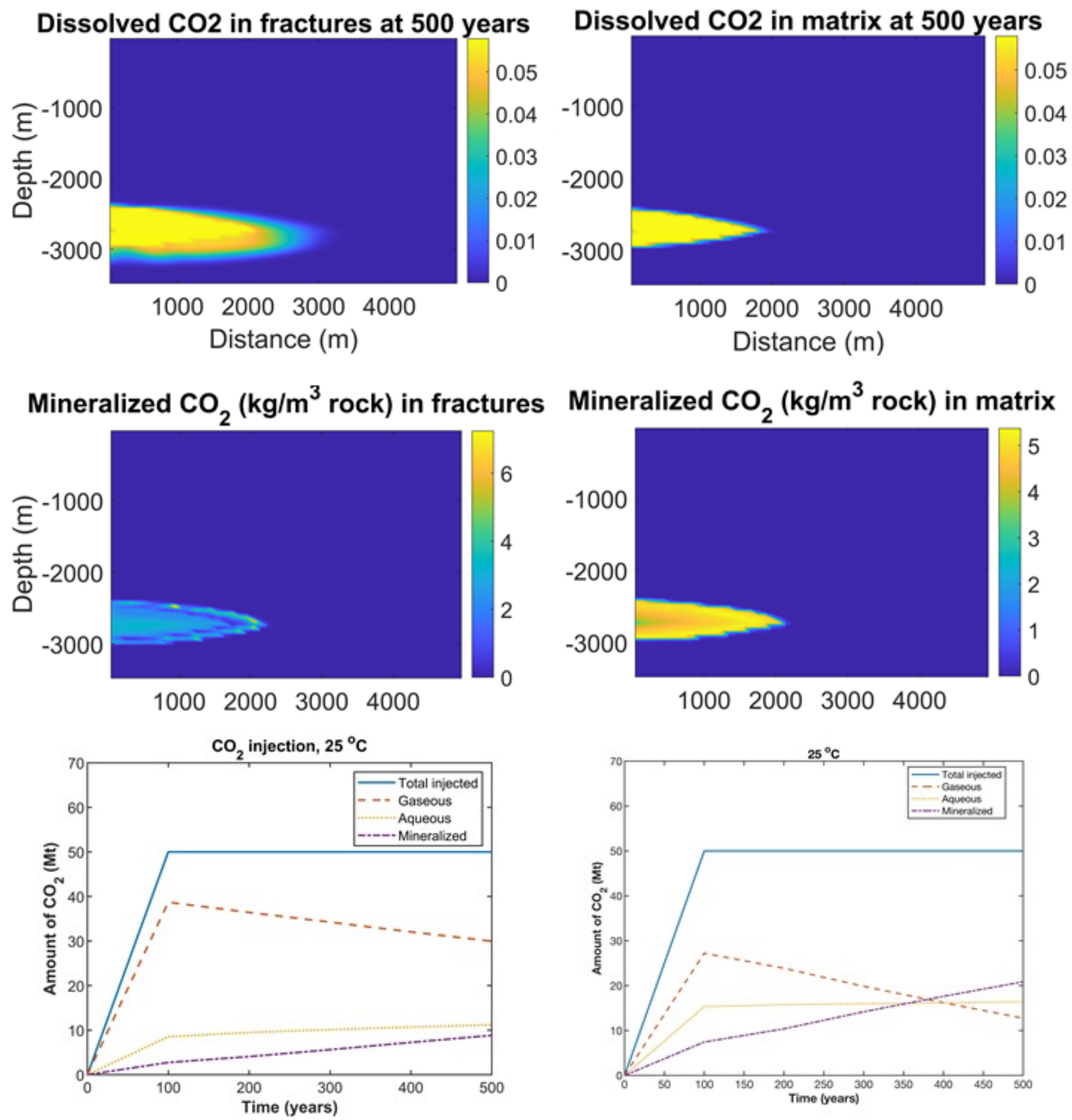












With dual permeability models CO_2 penetrates farther out into formations and mineralization is enhanced

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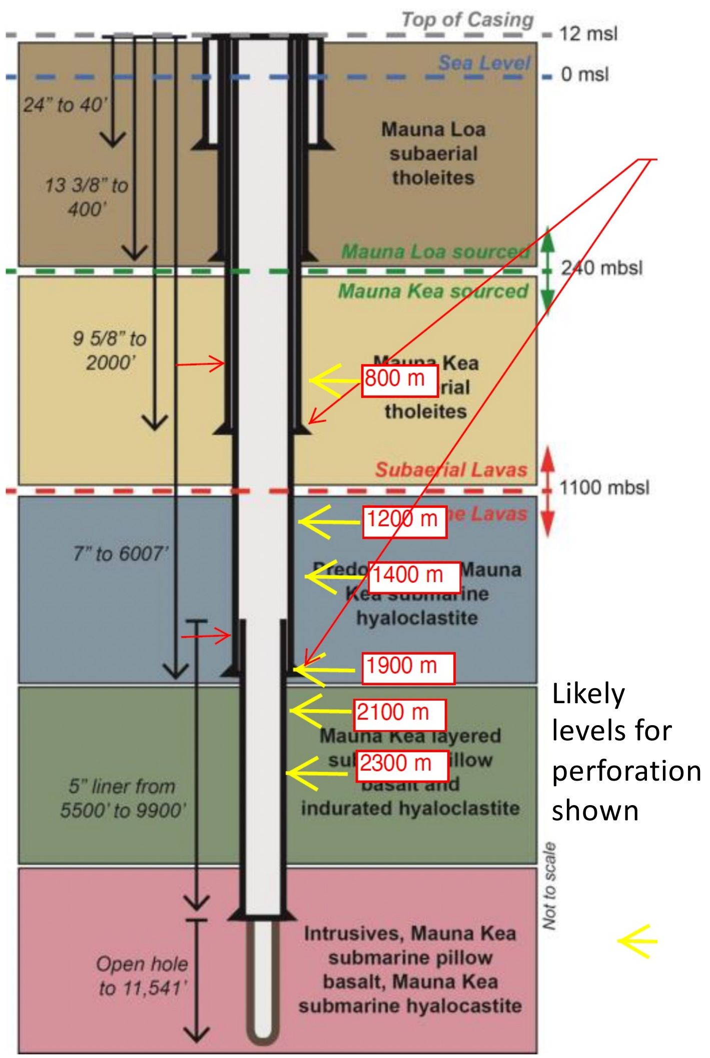
Subsurface Carbon mineralization resources in Hawaii Basalt (current project starting 2023)



New project is focused on

1. Downhole logging, sampling, and injection testing using the HSDP 3500m deep well
2. Perforating casing to allow sampling of fluid at different levels and pull-push-pull tests to evaluate reactivity and injectivity
3. Geophysical imaging of subsurface reservoirs using ambient seismicity
4. Geochemical characterization of formation fluids from specific depth intervals
5. Reactive transport modeling of trapping and mineralization
6. Hydrogeologic modeling of ambient circulation and impacts of injection
7. Laboratory experiments on glassy basaltic clastic rocks from the section

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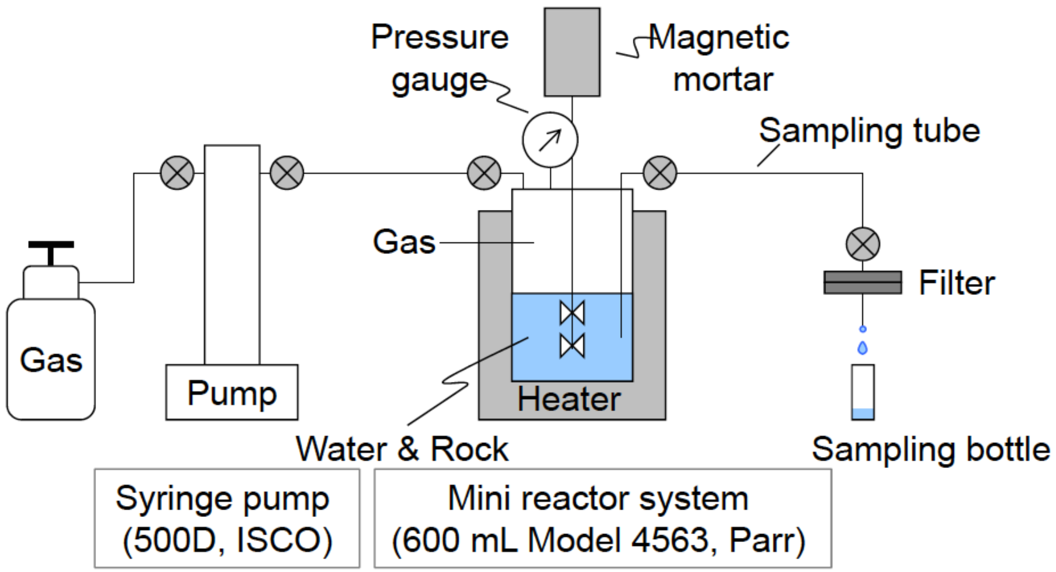
Evaluating mineralization rates with dissolution experiments



Lake County Labradorite
An_{67} (collected for this work)

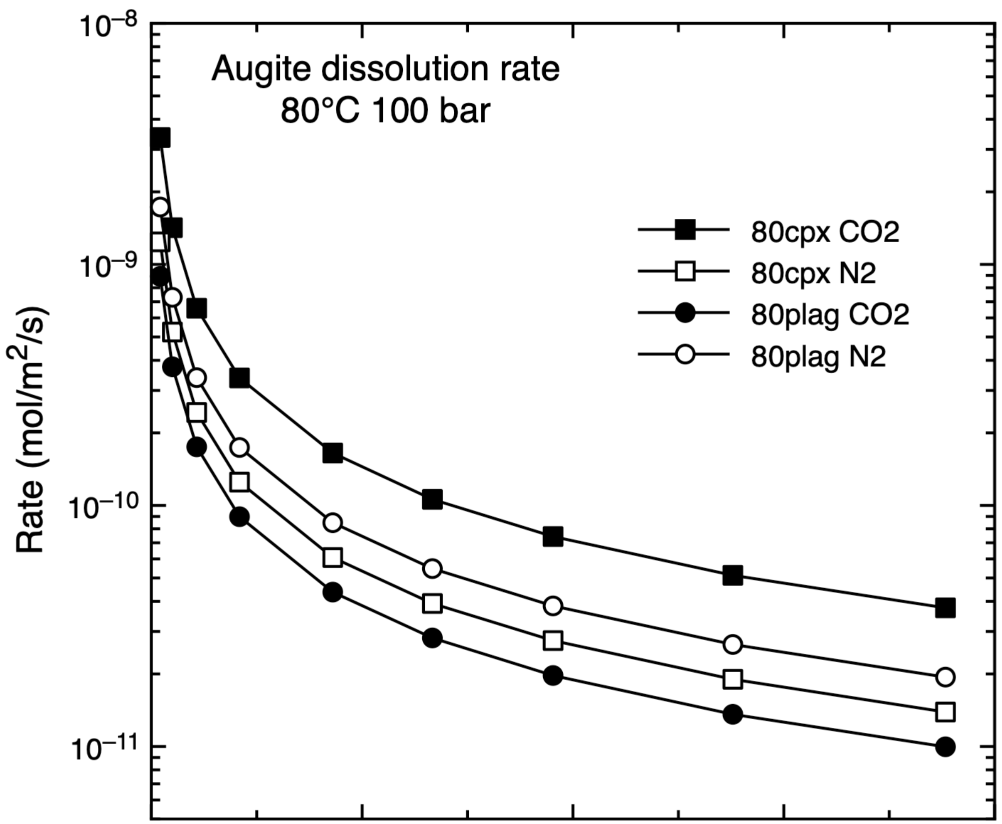
Wards Augite
Ca:Mg:Fe = 47:35:18

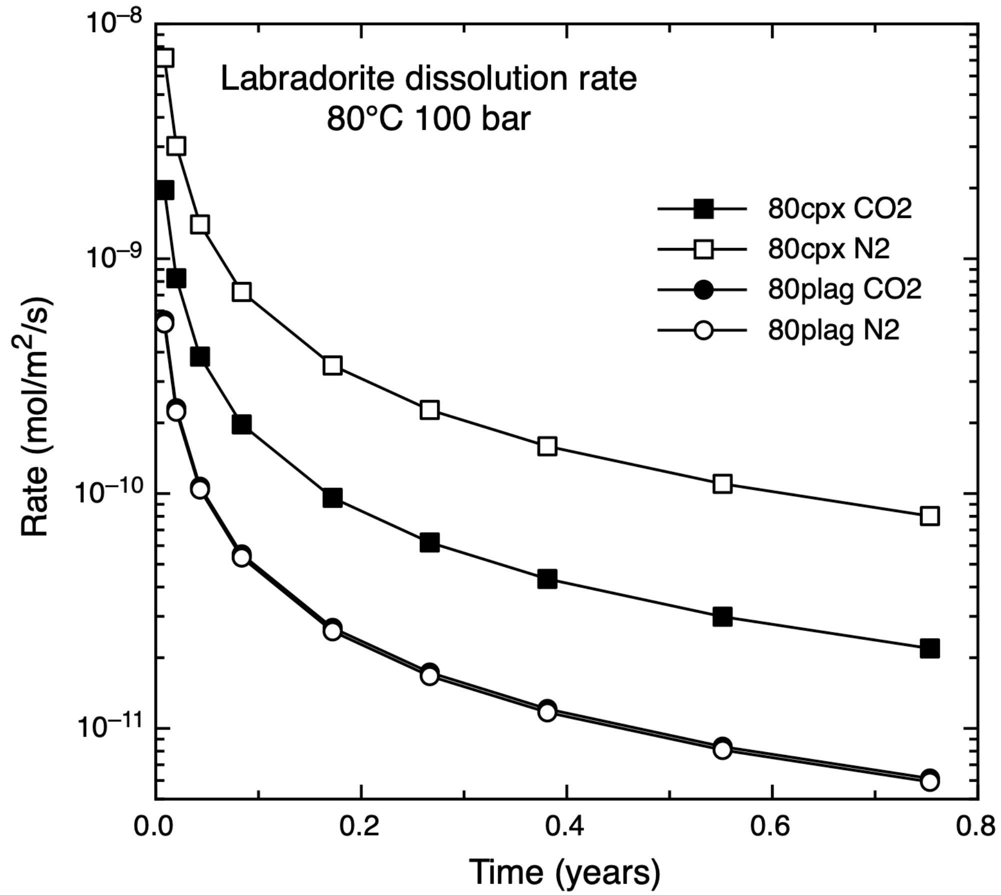
45 – 90 µm size fraction

Closed-system experiments performed at RITE

1. 30g solid with 300g fluid
2. Fluid has seawater Na, Cl, Mg (no Ca, Fe, Si, etc)
3. Fluid sampled at varying intervals, 10 samples per experiment over 275 days
4. *Time correction* made to account for decreasing fluid volume from sampling
5. Fluids measured for Ca, Mg, Fe, Si, Al, and trace elements Mn, Sr, Ba
6. **4 experiments at 80°C and 100 bar**
   80 CPX:20 Plag w/ N_2 and CO_2 atmosphere
   80 Plag:20 CPX w/ N_2 and CO_2 atmosphere
7. Measured Sr/Ca used to determine proportions of minerals dissolving
   ($Sr/Ca_{plag} \approx 13 \times Sr/Ca_{cpx}$)
8. Calculations assume geometric surface area
   (24 m^2/kg for CPX; 31 m^2/kg for Plag)

Simple analysis: [Ca] data fit with logarithmic functions





These curves show the dramatic decrease in dissolution rate during the experiments

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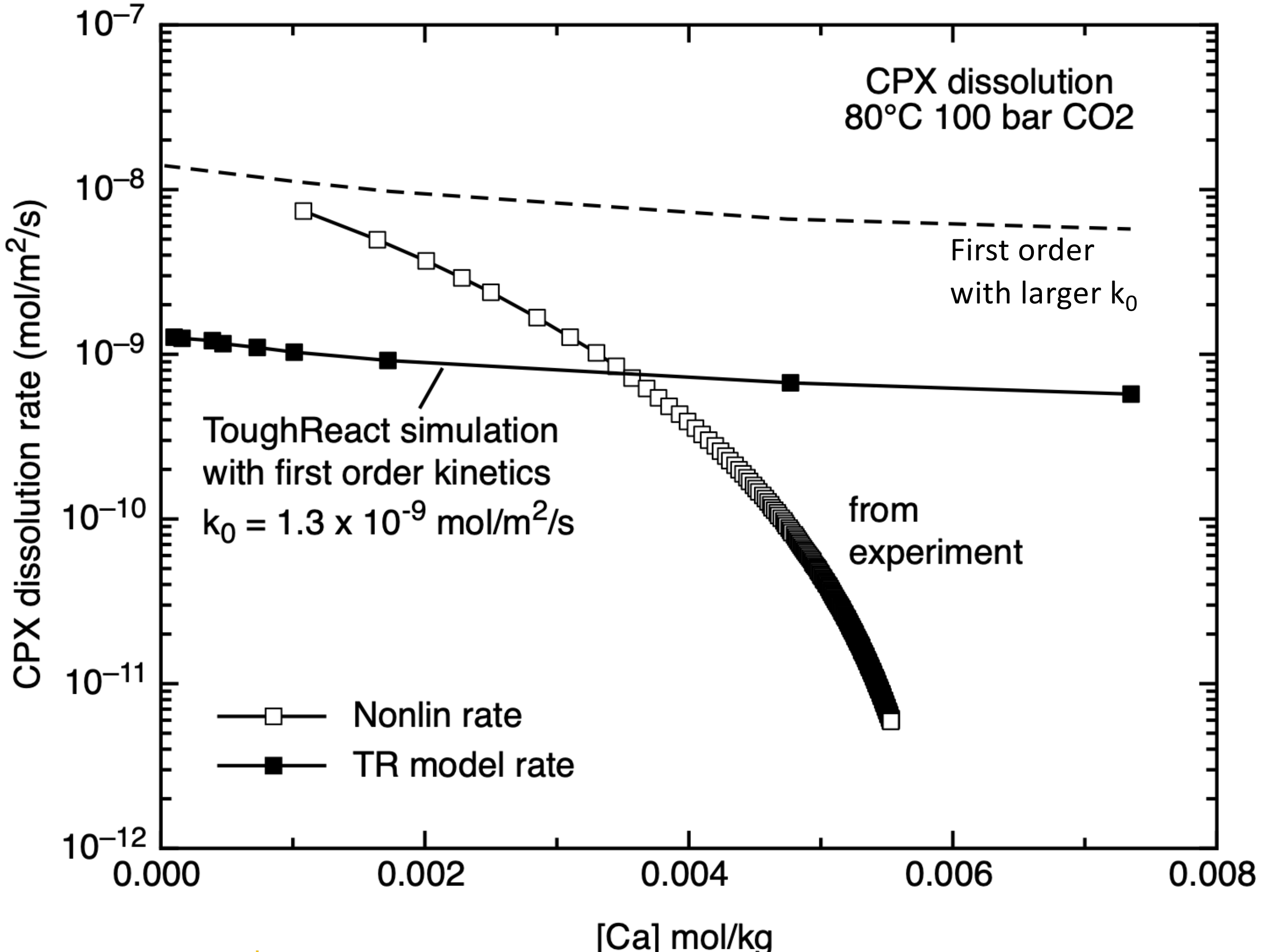
Implications for CO_2 mineralization rates: Limitations of 1st order kinetics in reactive transport models



Our experiments were also simulated (approximately) using ToughReact with 1st order kinetics

The simulations account for secondary mineral formation and all components in solution

1st order kinetics produces some slowing of dissolution as [Ca] increases in solution, but **does not capture the 1000x slowing** found in the experiments

Implications for CO_2 mineralization rates: Limitations of 1st order kinetics

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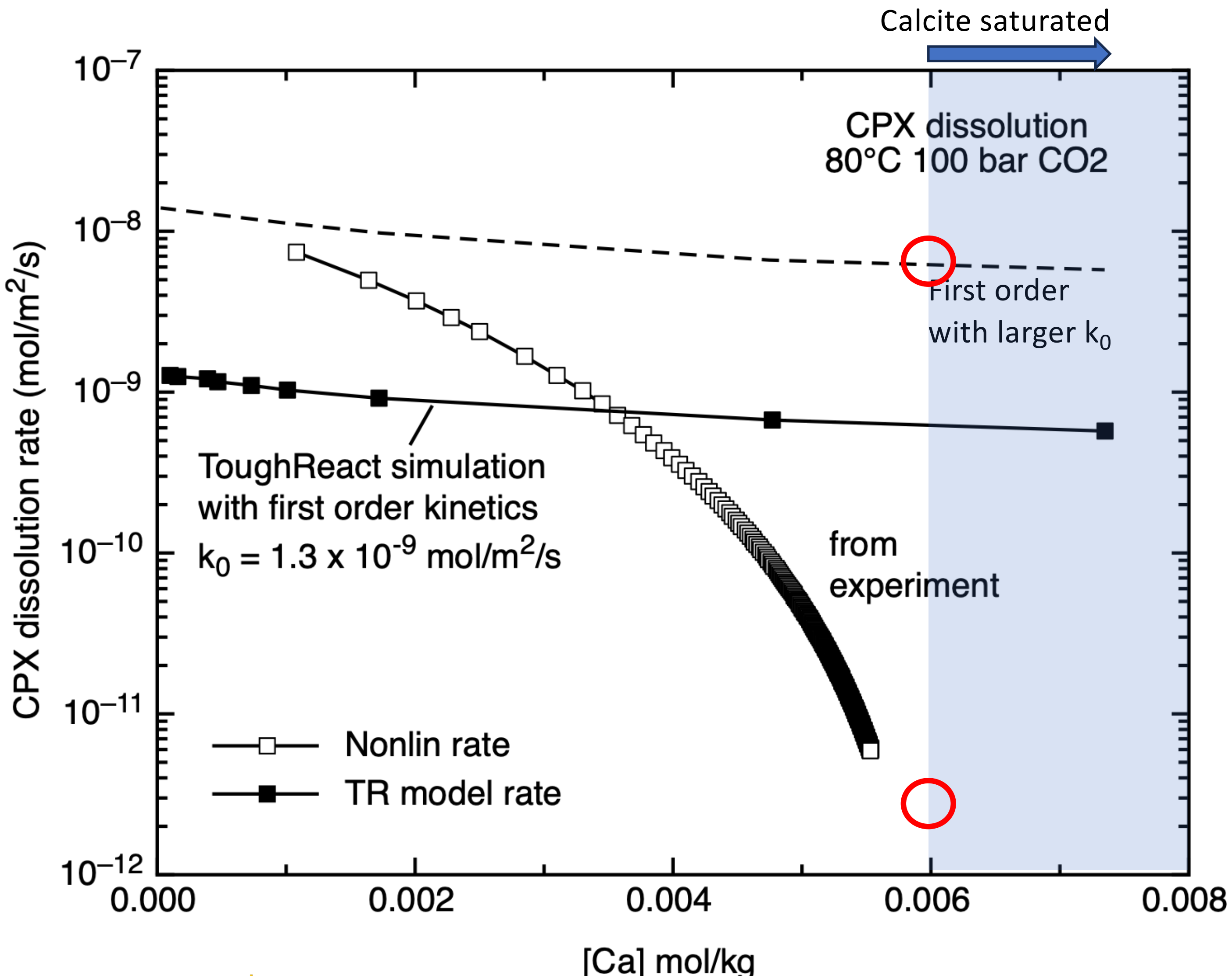


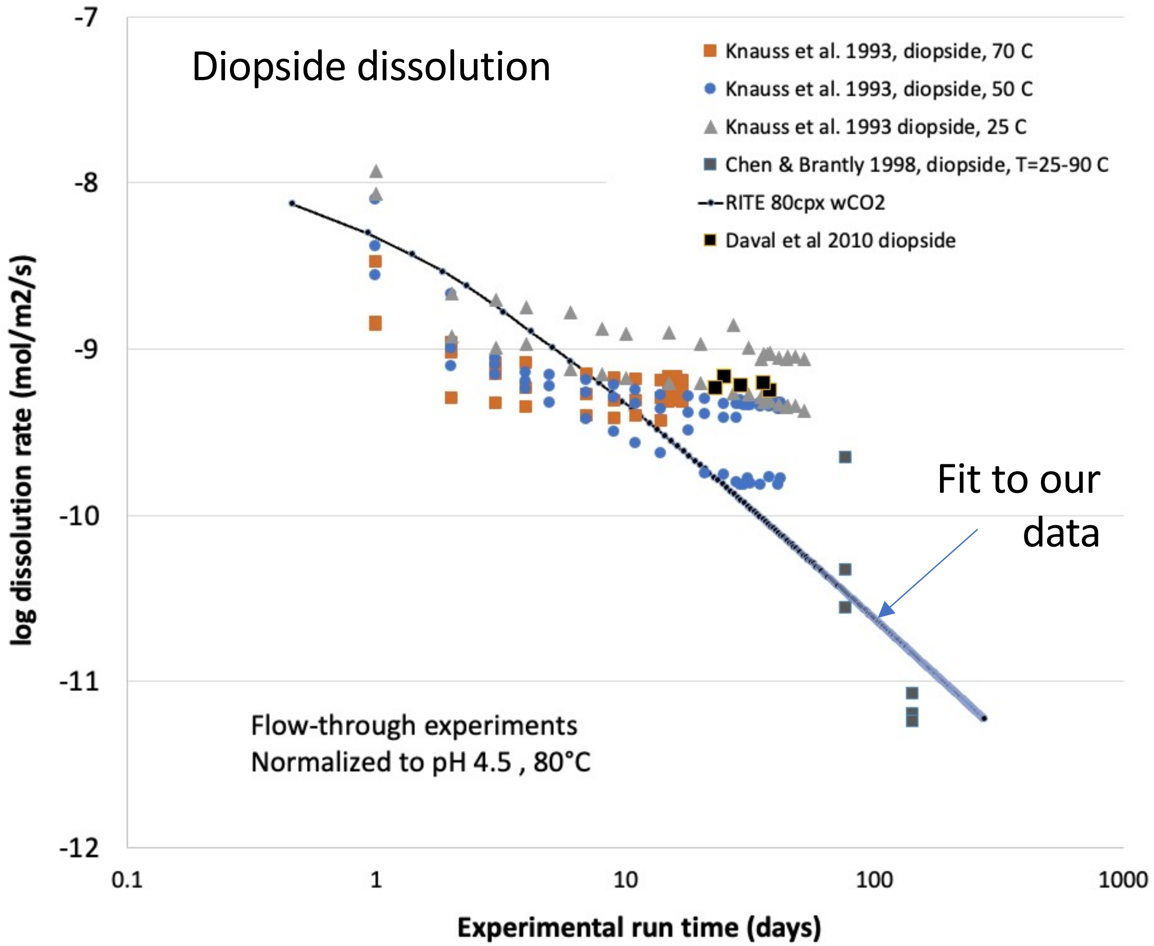
Using the same value of $k_0 = 1.4 \times 10^{-8}$ mol/m²/s

And estimating that calcite would become saturated at [Ca] = 6 mmol (from reservoir scale simulations of Zhang et al., 2015, and Zhang and DePaolo, 2017)….

CPX dissolution rate at calcite saturation could be > 1000 x slower than estimated from 1st order kinetics

Behavior of plagioclase dissolution is similar

Open system (flow through) experiments from literature also suggest time-dependence of dissolution rates



Data compilation by Shuo Zhang

There is evidence that mineral reactivity decreases with time even in the absence of changing fluid chemistry

The only real tests of the aging effect are in natural systems, where we know that it looks real (e.g White et al., 2017)

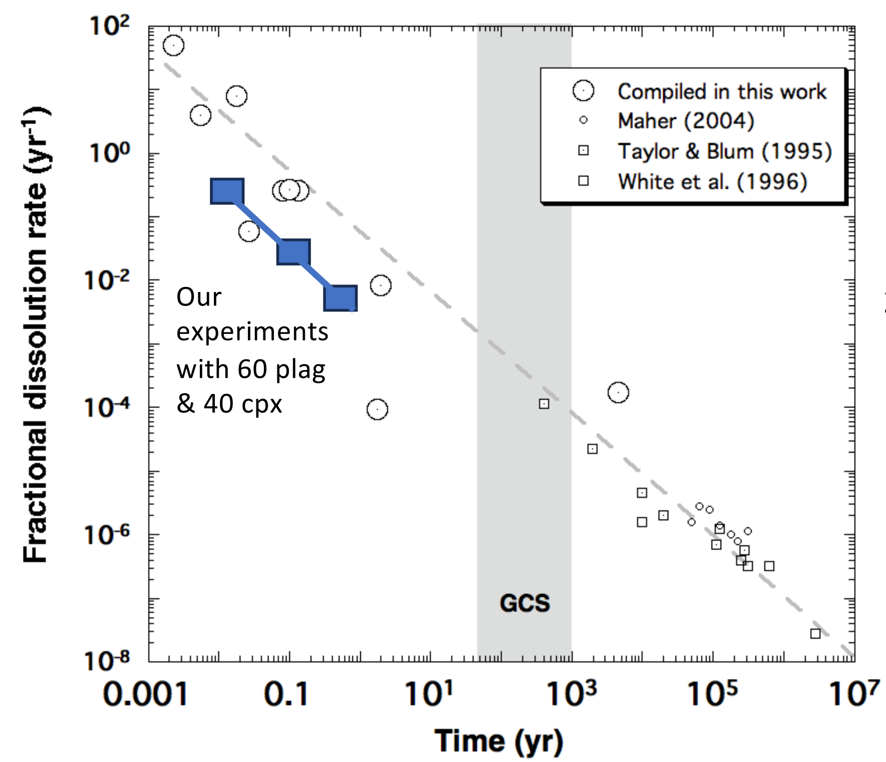
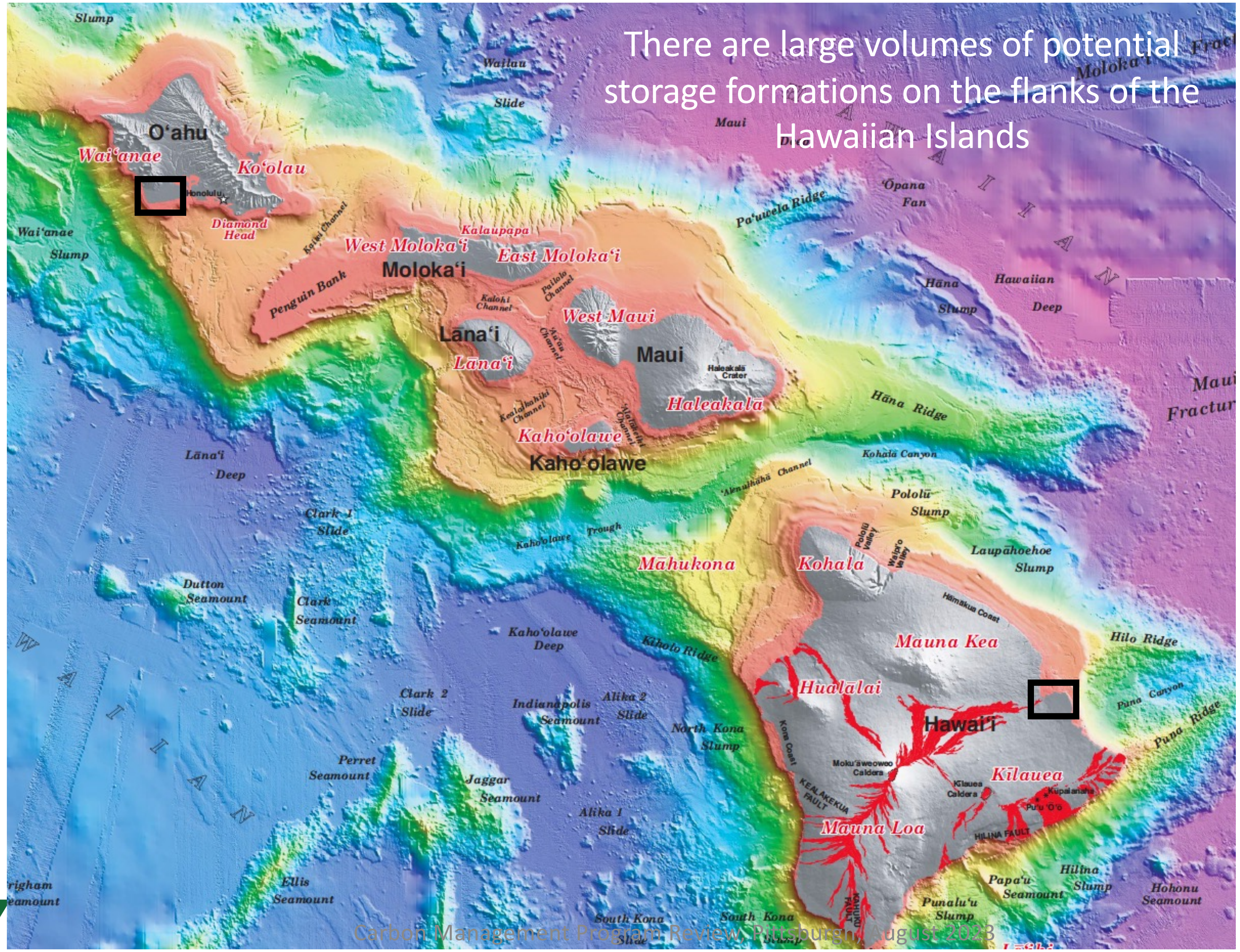


Figure from Zhang and DePaolo (2017)

Other targets for evaluation

2/3 of Hawaii emissions are from Oahu (5 Mton/y)



Key questions for proof of concept

1. What is the likely range of **vertical permeability** in submarine volcanic sections?
2. What is a likely range of horizontal permeability, how much **interconnected pore space** is typical, and on what length scales?
3. How efficient is **capillary trapping** in basalt or andesite lava flows?
4. Can **mineralization rates** be adequately estimated? What is the tradeoff between CO_2 density (low-T; high-P) and mineralization rates?
5. Can storage capacity be estimated? Are glass-rich horizons effective **seals**? Are they self-sealing?
6. How effective is **hydrate formation** as a CO_2 trapping mechanism?
7. Does the combination of characteristics and multiple trapping mechanisms ensure **permanent storage**?

Disposing of HCl and/or concurrent disposal of HCl and CO_2

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Direct electrosynthesis of sodium hydroxide and hydrochloric acid from brine streams

Amit Kumar[1,2,5]*, Katherine R. Phillips[3,5], Gregory P. Thiel[1,2], Uwe Schröder[4] and John H. Lienhard V[1,2]*

A proposed approach to de-acidifying the oceans is to

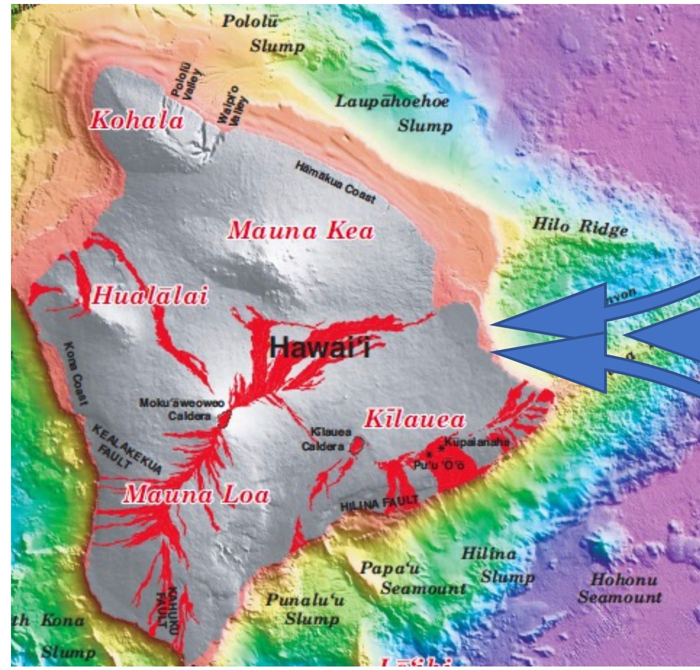
1. use electro-hydrolysis to produce NaOH and HCl from seawater or from saltwater residue from desalination
2. put the NaOH back into the ocean to increase its pH and allow it to dissolve additional CO_2 from the atmosphere
3. dispose of the HCl by reacting it with rocks (like basalt)

Question 1 is whether basalt, as in Hawaii, could be used for HCl disposal (0.5 M HCl if from seawater, more concentrated if from desalination)

Question 2 is whether HCl and CO_2 disposal could be combined

Question 3 is whether concurrent HCl and CO_2 disposal could be used somehow to increase the mineralization rate of CO_2

CO_2 imported by tanker



HCl from seawater hydrolysis

CO_2 from DAC, H_2 generation, and BECCS (?)

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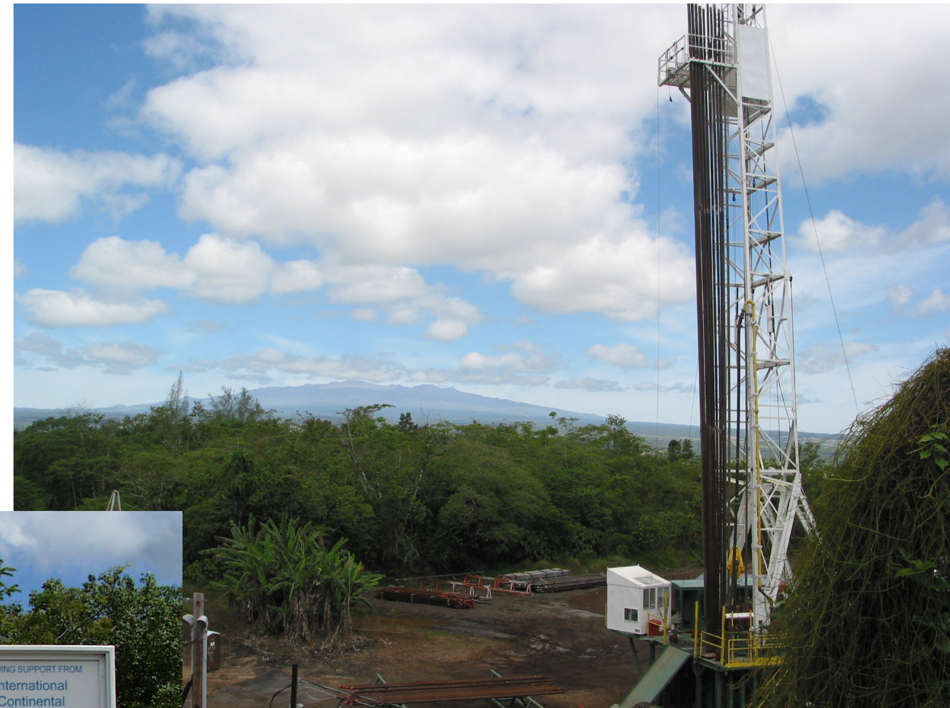

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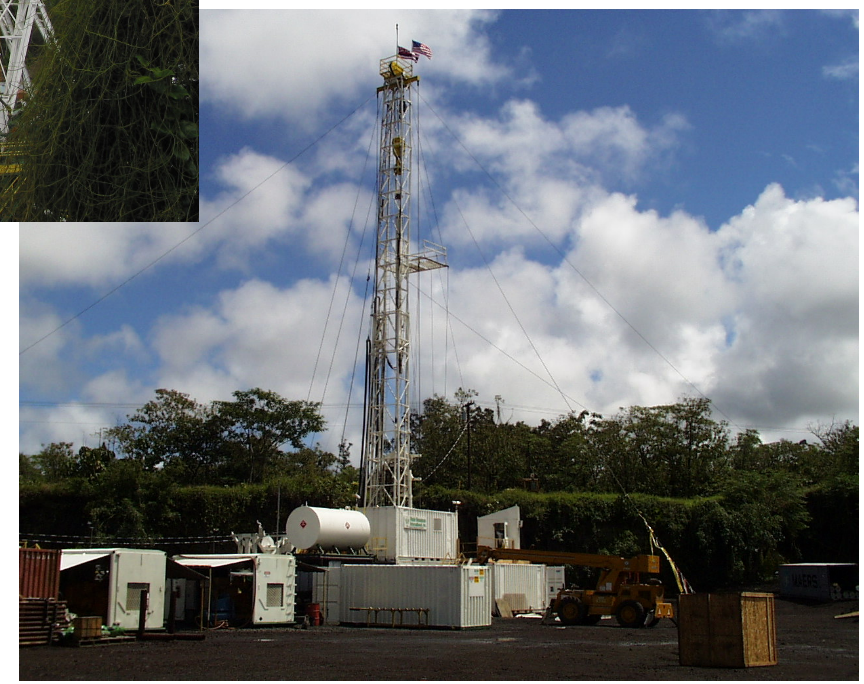

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