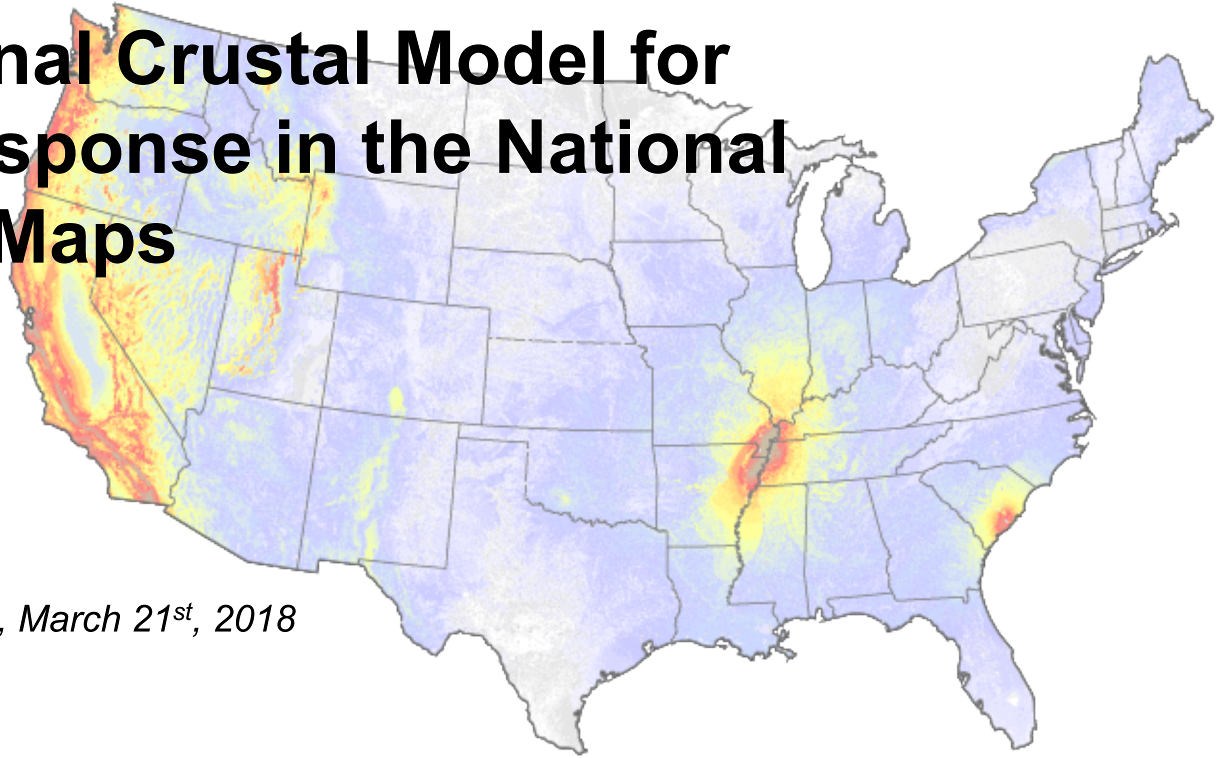
The USGS National Crustal Model for improved site response in the National Seismic Hazard Maps



Presented by Oliver Boyd

U.S. Geological Survey

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U.S. Department of the Interior
U.S. Geological Survey

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- **Tom Brocher**—*Well logs*
- **Brad Aagaard, Scott Callaghan, Bill Stephenson, Morgan Moschetti**—*3D crustal models in California, Seattle, and the Wasatch Front*
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- **Jeremy Boak and Jake Walter**—Oklahoma
- **Alexandros Savvaidis**—Texas

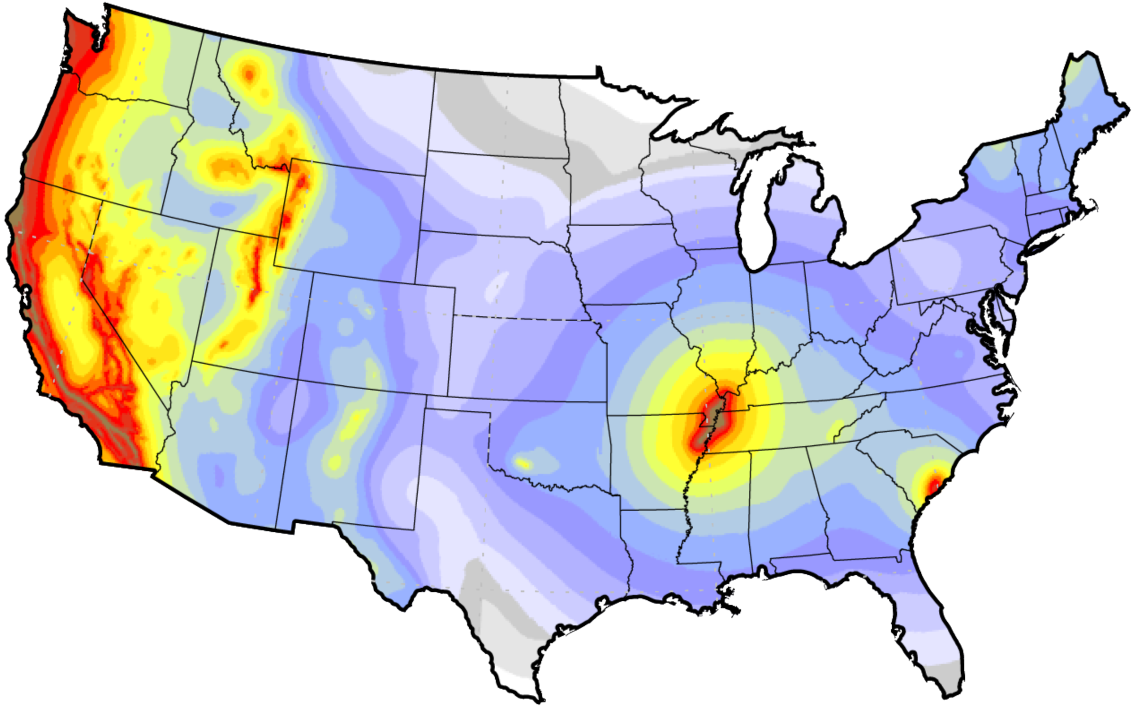
Outline

- Motivation
  - Where we are and where we want to be
- National Crustal Model (NCM)
  - What is it?
  - Purpose
  - Construction
  - Calibration
  - Validation

Motivation

USGS National Seismic Hazard Model: 2014

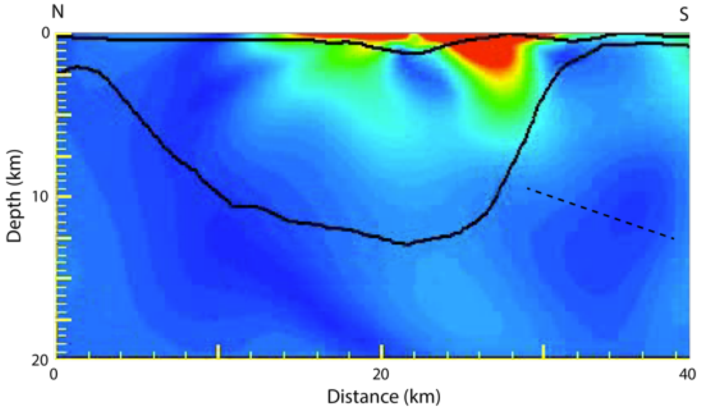
- Uniform site condition
- No path effect
- Minimal regionalization of ground motion prediction equations



Effect of Local Geology

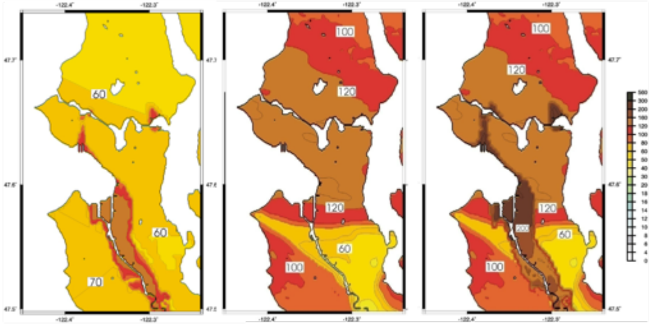
Urban Hazard Mapping

For Seattle, Frankel et al. (2007) compute the hazard from a set of large magnitude sources specific to the Seattle area with 3-D ground motion simulations.



Effect of Seattle Basin on ground motion amplitudes 2 seconds after a simulated M6.5 earthquake on the Seattle Fault (dashed line) [Frankel and Stephenson, 2000].

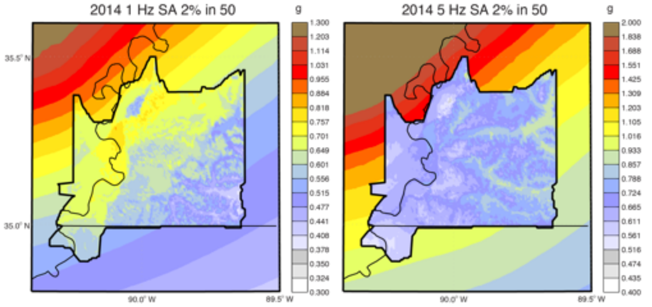
1 Hz spectral acceleration (g) with a 2% chance of being exceeded in 50 years in Puget Sound



2002 National Seismic Hazard Maps with NEHRP Amplification Factors | Including 3-D simulations with basin effects and directivity | 3-D simulations and non-linear amplification for fill and alluvium

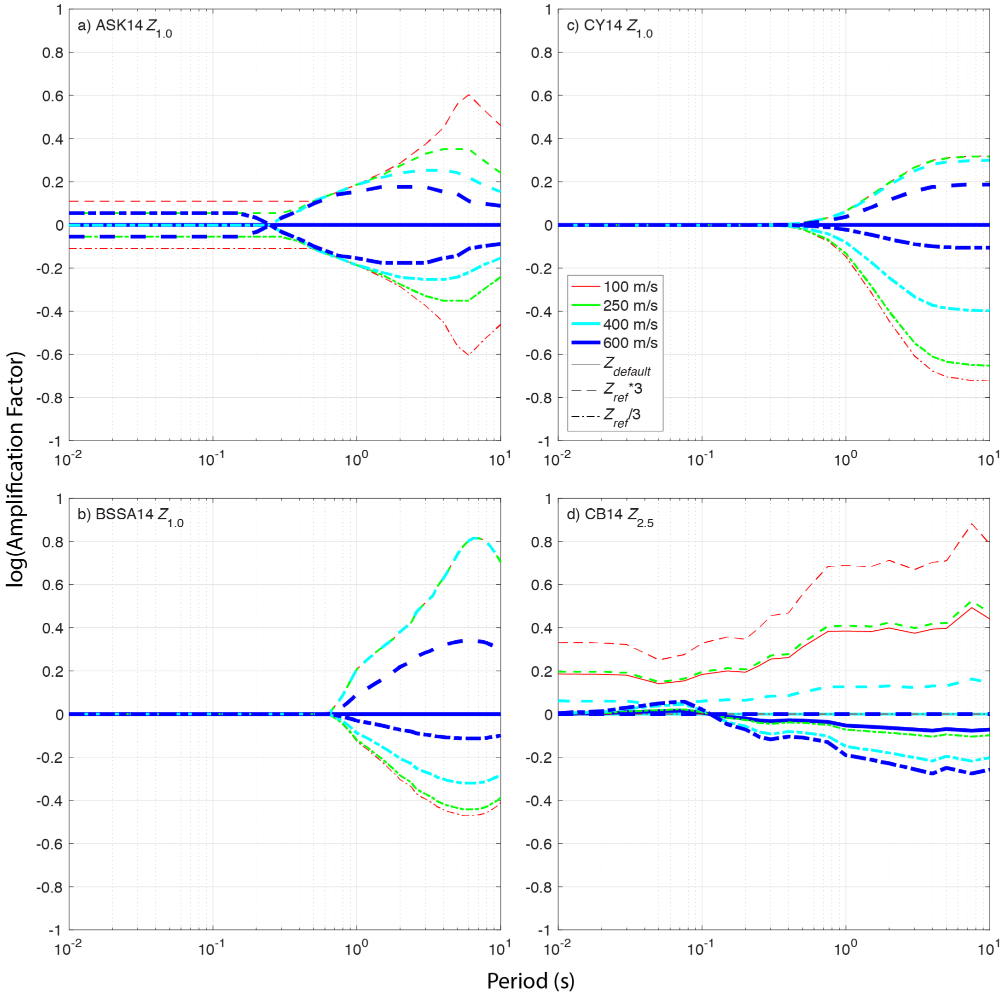
For Memphis, Cramer et al. (2014) used sources from the 2014 USGS National maps with ground motions modified by 1D vertical propagation through a 3-D velocity model.

Shelby County, Tennessee



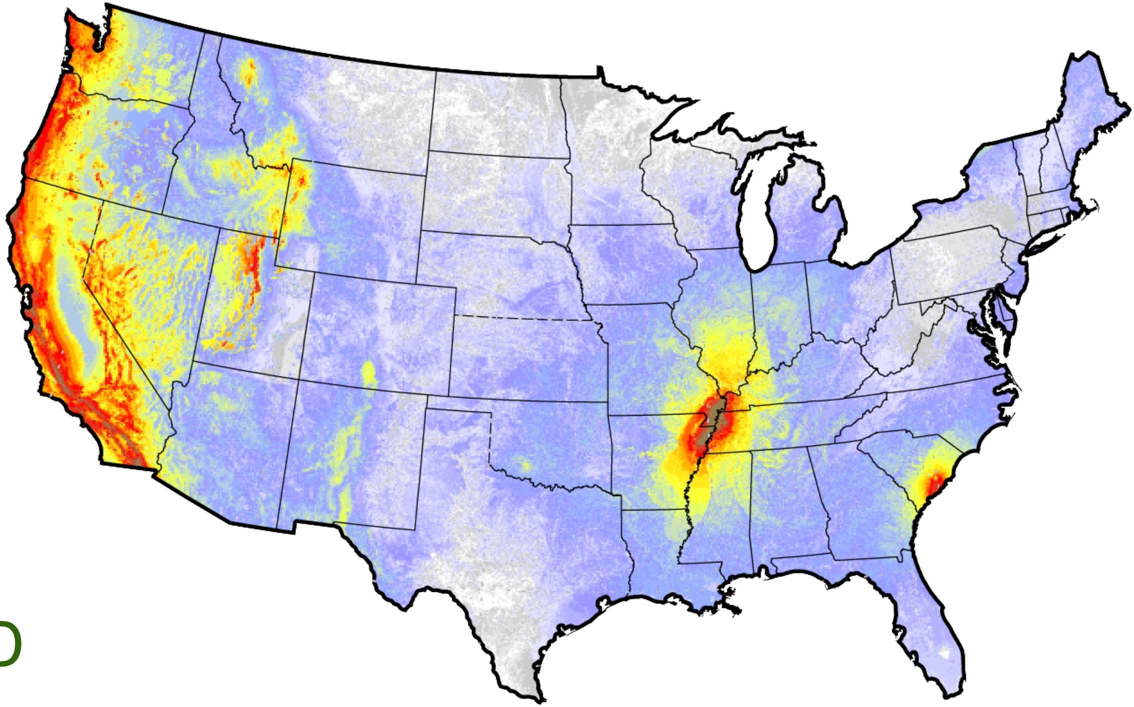
Ground Motion Prediction Equations

- Site response parameters including V_{S30}, $Z_{1.0}$, and $Z_{2.5}$



USGS National Seismic Hazard Model: 20??

- Provide site response metrics to current GMPEs uniformly across the US.
- Prepare for future site response metrics, regionalization, and 3D simulation.

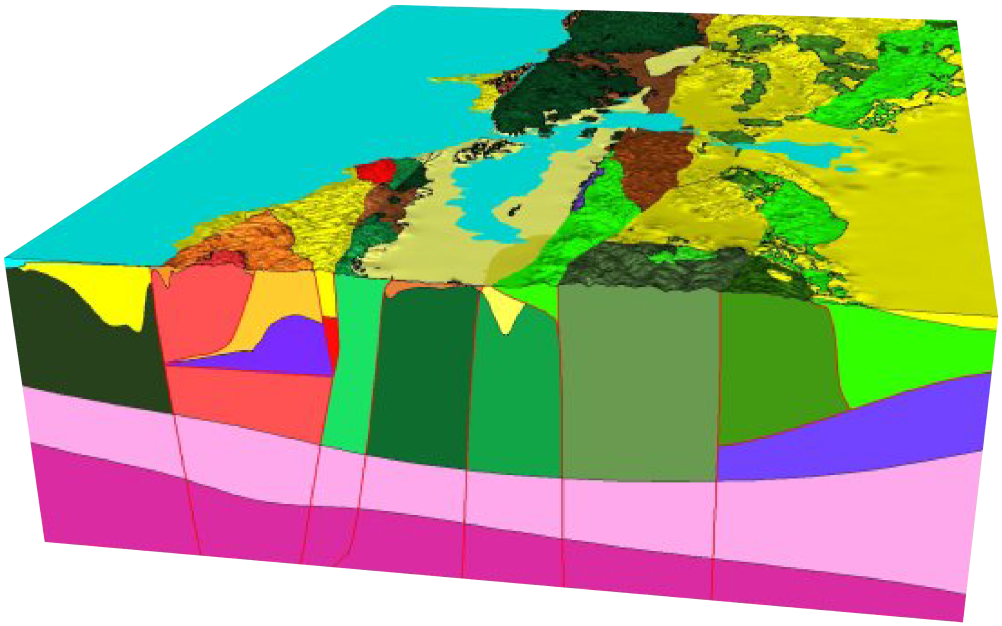


Building a National Crustal Model

Existing Crustal Models

Examples

- Bay Area
- Southern California
- Seattle
- Wasatch Front
- Upper Mississippi Embayment



Aagaard et al., 2010

National Geologic Mapping Program
(2030 goal to produce a National 3D model)

USGS National Crustal Model

- What is it?
  - Profiles defined on 1-km grid across the conterminous United States
    - Geology and petrology
    - Geophysics
      - *K, Bulk Modulus*
      - *G, Shear Modulus*
      - ρ*, Density*
      - ϕ*, Porosity*
      - Q_P*, P-wave attenuation*
      - Q_S*, S-wave attenuation*

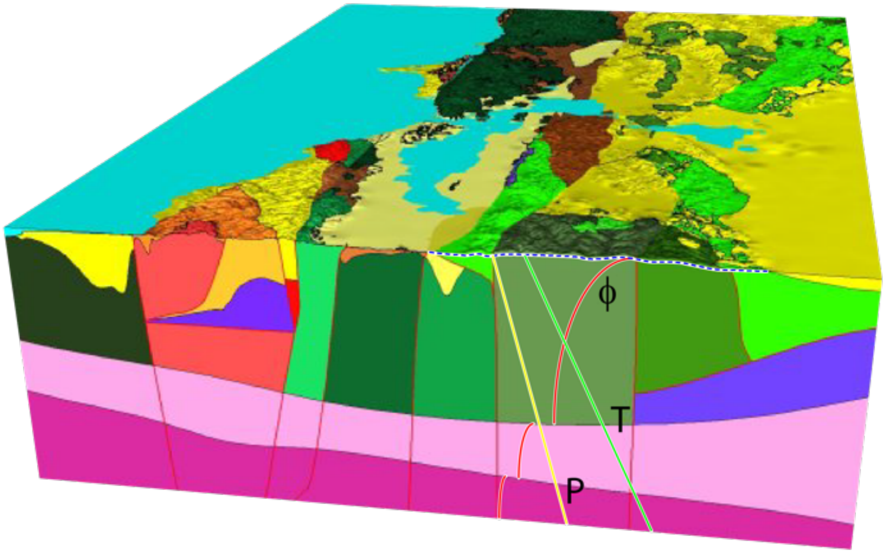
USGS National Crustal Model

- Purpose
  - Provide metrics for GMPEs (**not for site specific analysis**)
    - Presently: V_{S30}, $Z_{1.0}$, and $Z_{2.5}$
    - Potentially: dominant period, full frequency- and amplitude-dependent 1D site response curve, spatially variable path-averaged attenuation and geometric spreading, and path-dependent finite-frequency focusing/defocusing.
  - Seismic attribute profiles and volumes for numerical ground motion simulations
  - Improved earthquake source analysis

USGS National Crustal Model

- Construction
  - Basic foundation:
    - Biot-Gassmann and mineral physics theory

      ➔ K, G, ρ
    - Porosity, pressure, and temperature as functions of depth
    - Water table depth
    - 3D Geologic Model



Adapted from Aagaard et al., 2010

NCM: Construction

– Porosity

- Assumed to be a function of differential pressure

$$\phi = \phi_0 \exp\left(-ap_N\right)$$

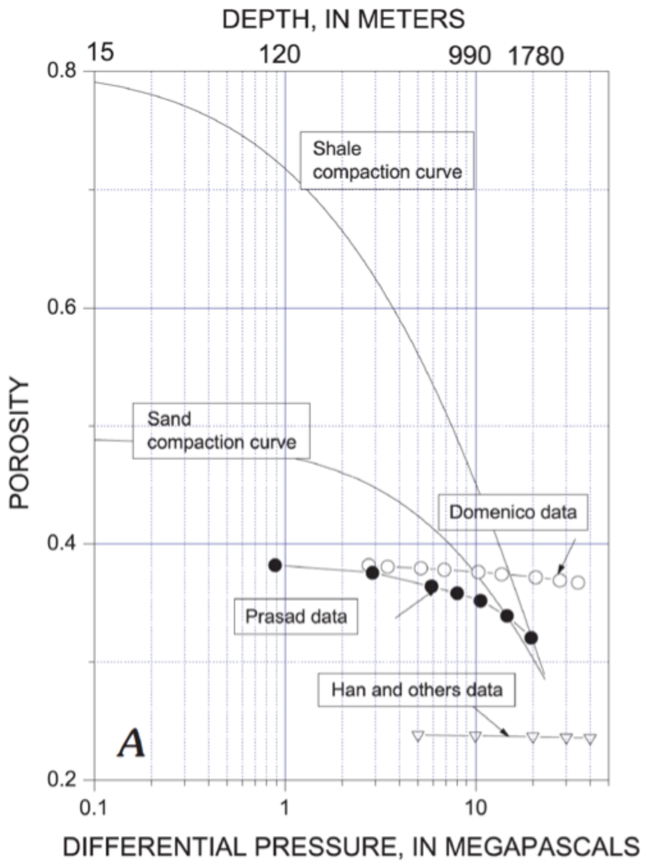


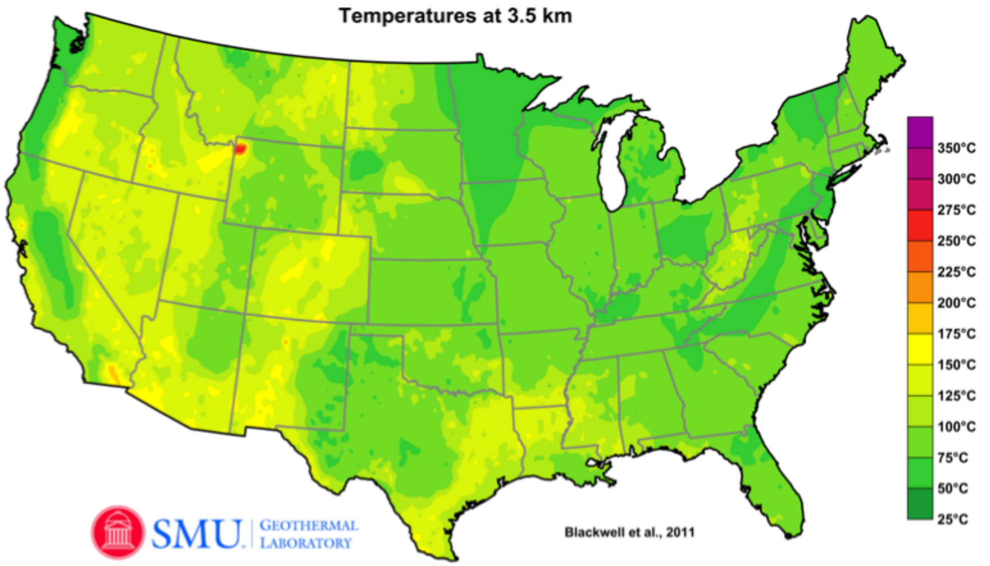
Figure 1A in Lee (2003)

NCM: Construction

- Temperature
  - Currently assume

    $$T = 300 + 0.022z$$

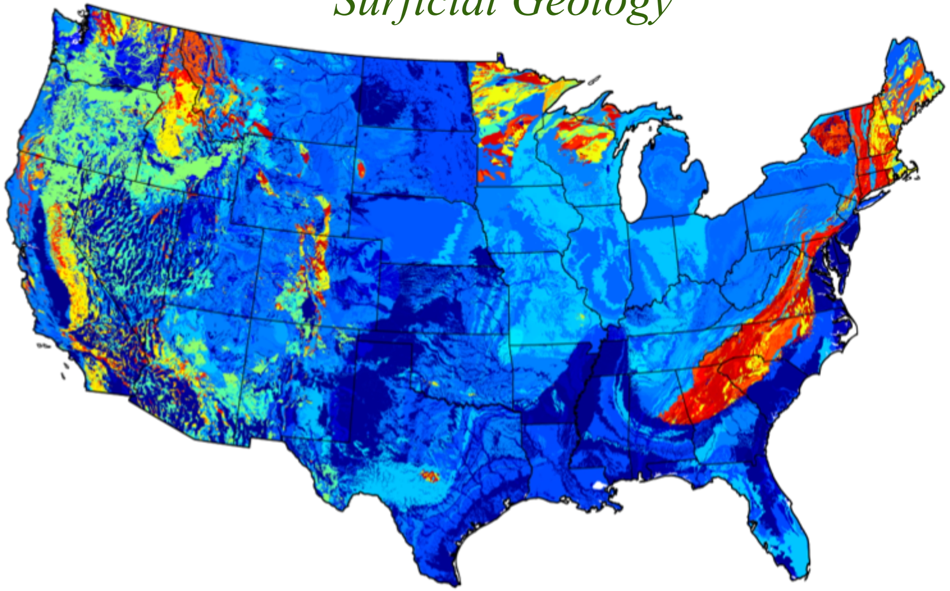
    but would like a 3D model such as that produced by SMU
- Pressure
  - Integrated weight of the material above



NCM: Construction

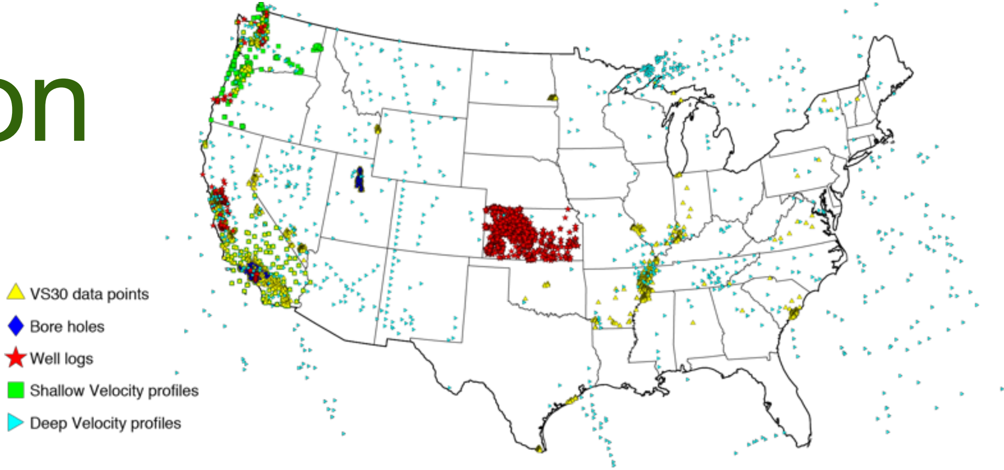
- 3D Geologic Model
  - Surficial porosity/composition
  - Maps of surficial, bedrock, and basement geology and age
  - Depths to bedrock and basement
  - Local 3-D geologic models, for example
    in the Bay Area and southern California.
  - Petrologic Model

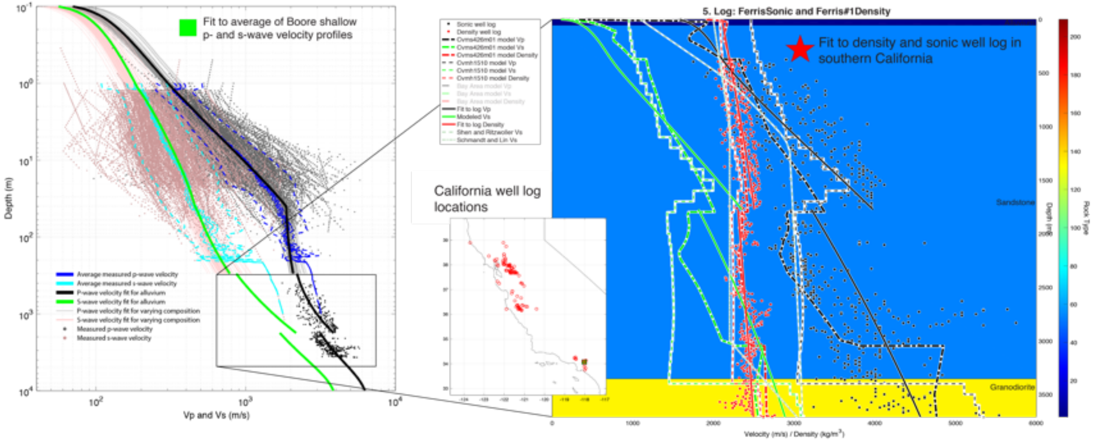
Surficial Geology



NCM: Calibration

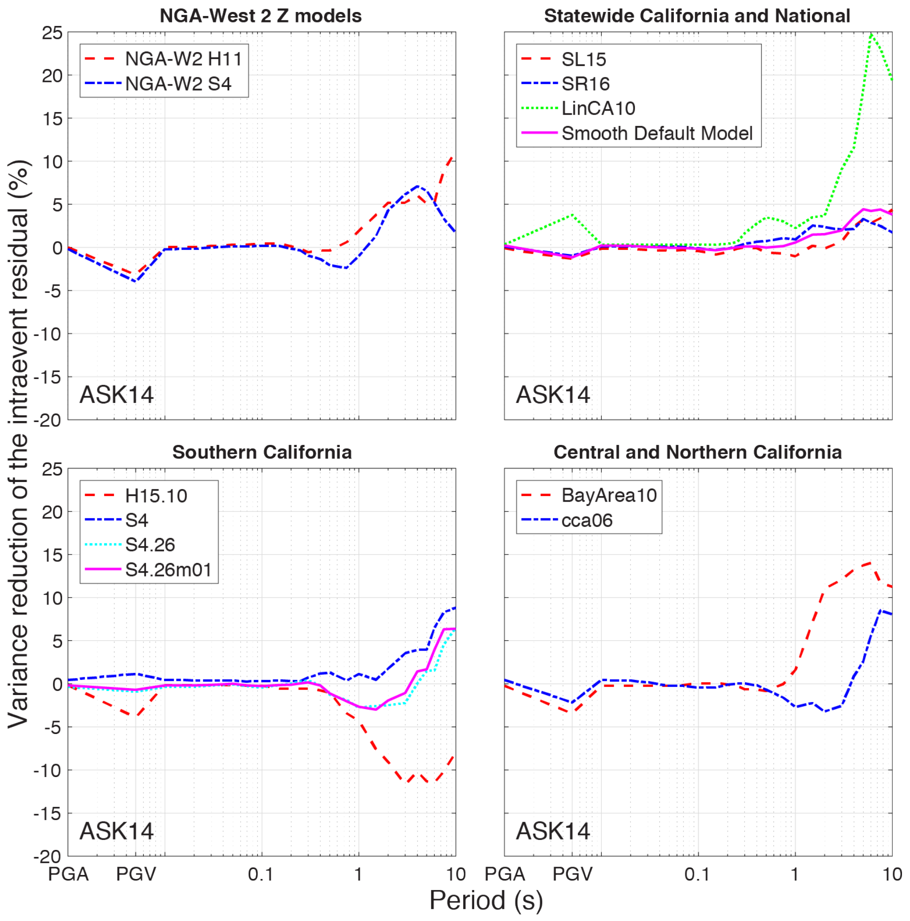
- Within the framework of Biot-Gassmann and mineral physics theory, calibrate
  - ϕ_0 and a in the porosity equation and α and m from Biot-Gassmann theory as functions of geology
- Using as constraints
  - Measurements of V_{S30}
  - Sonic logs
  - Density logs
  - Shallow and deep velocity profiles





NCM: Validation

- Using current GMPEs and values of V_{S30}, $Z_{1.0}$, and $Z_{2.5}$ from the NCM, estimate ground motions in the NGA-West 2 dataset.
- Model ground motion time series with 2D and 3D simulations.



Conclusions

- Western US (for 2020 NSHM)
  - Complete calibration
  - Validation
    - Using the NGA-West 2 dataset
  - Estimate uncertainty
  - Published by June 2018 for Z mapping application

Conclusions

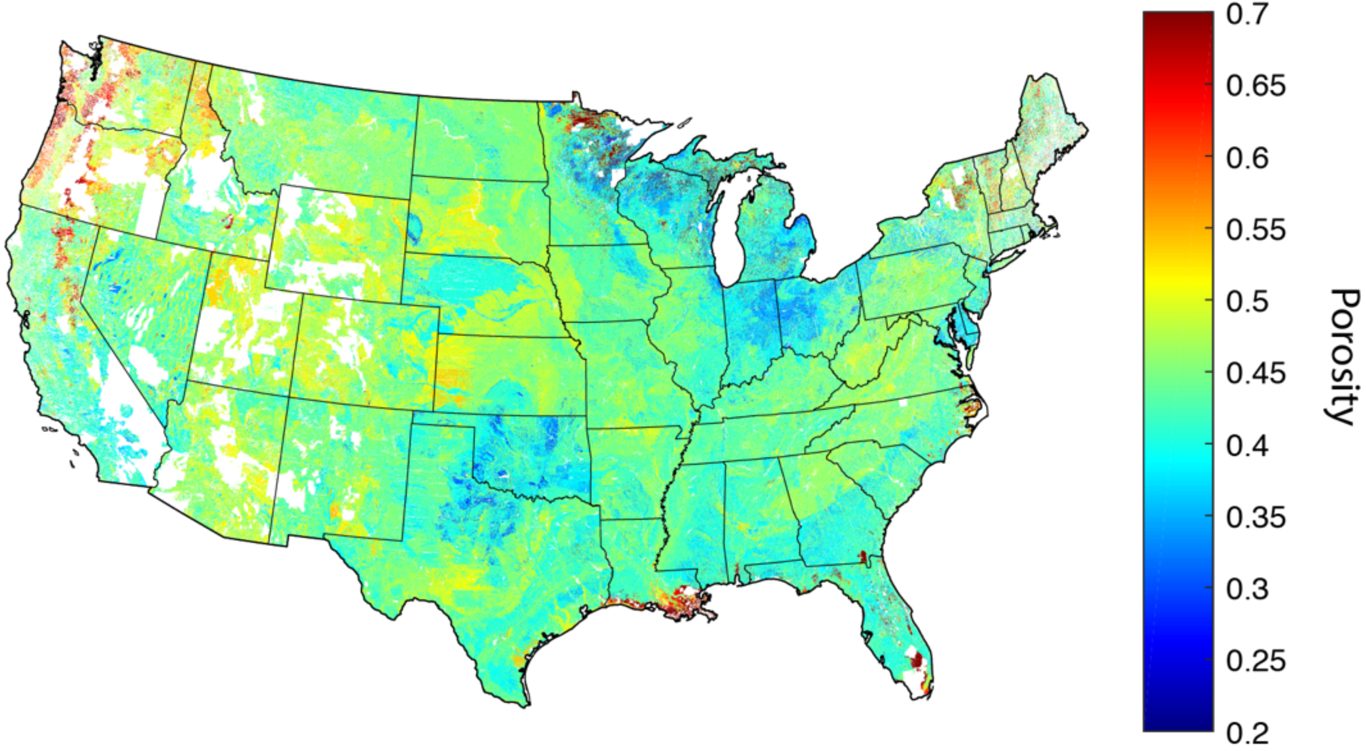
- Western US (beyond 2020 NSHM)
  - Model improvements
  - Validation
    - Ground motion simulations
- CEUS in FY19

Details: Input

Significant room for improvement

Surficial Porosity

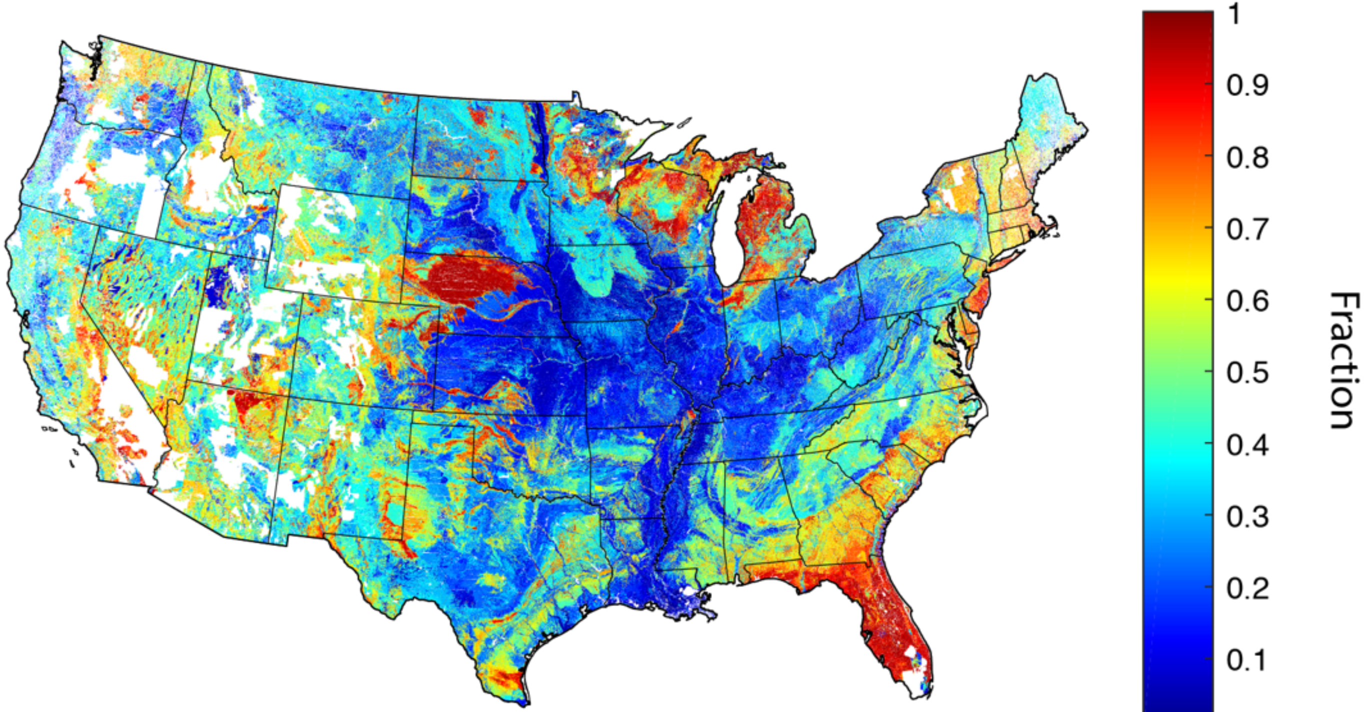
- Porosity derived from the National Cooperative Soil Survey (SSURGO)



NCSS not defined in all areas.

Surficial Sand Fraction

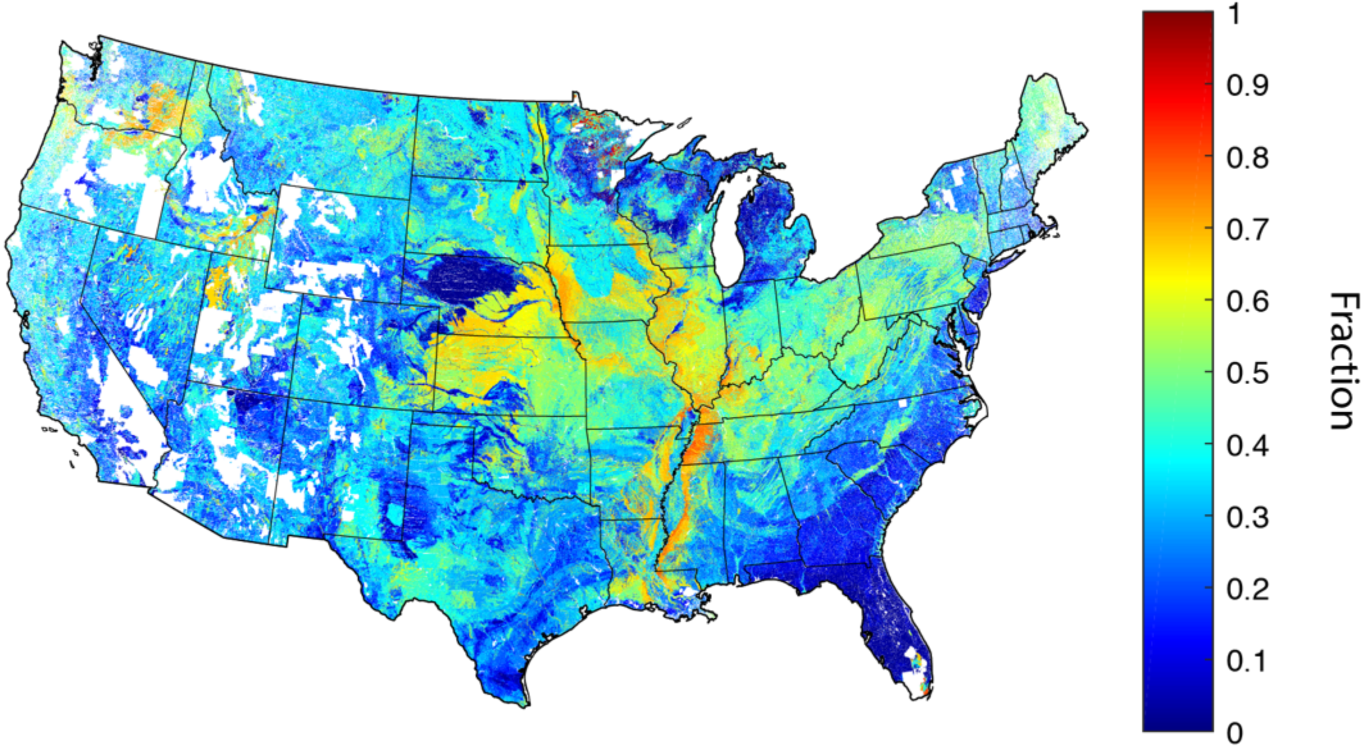
- Sand content obtained from the National Cooperative Soil Survey



NCSS not defined in all areas.

Surficial Silt Fraction

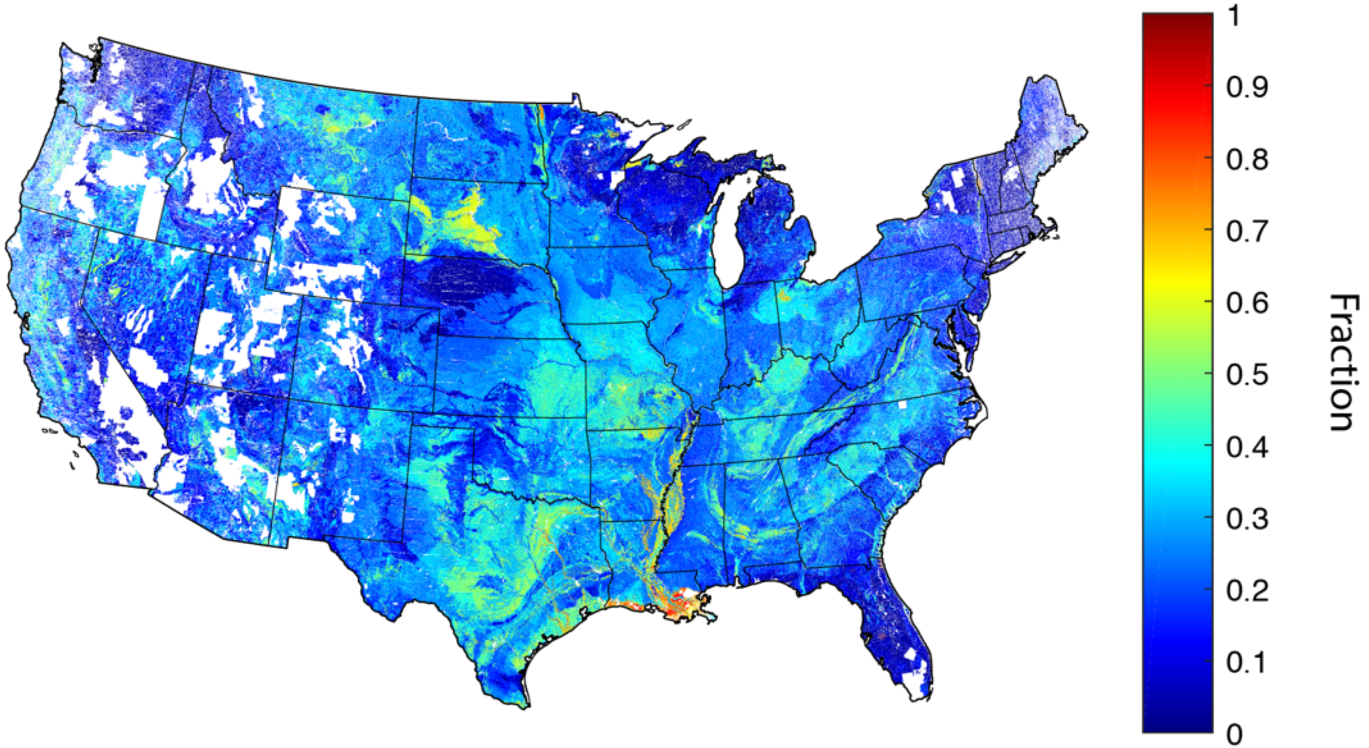
- Silt content obtained from the National Cooperative Soil Survey



NCSS not defined in all areas.

Surficial Clay Fraction

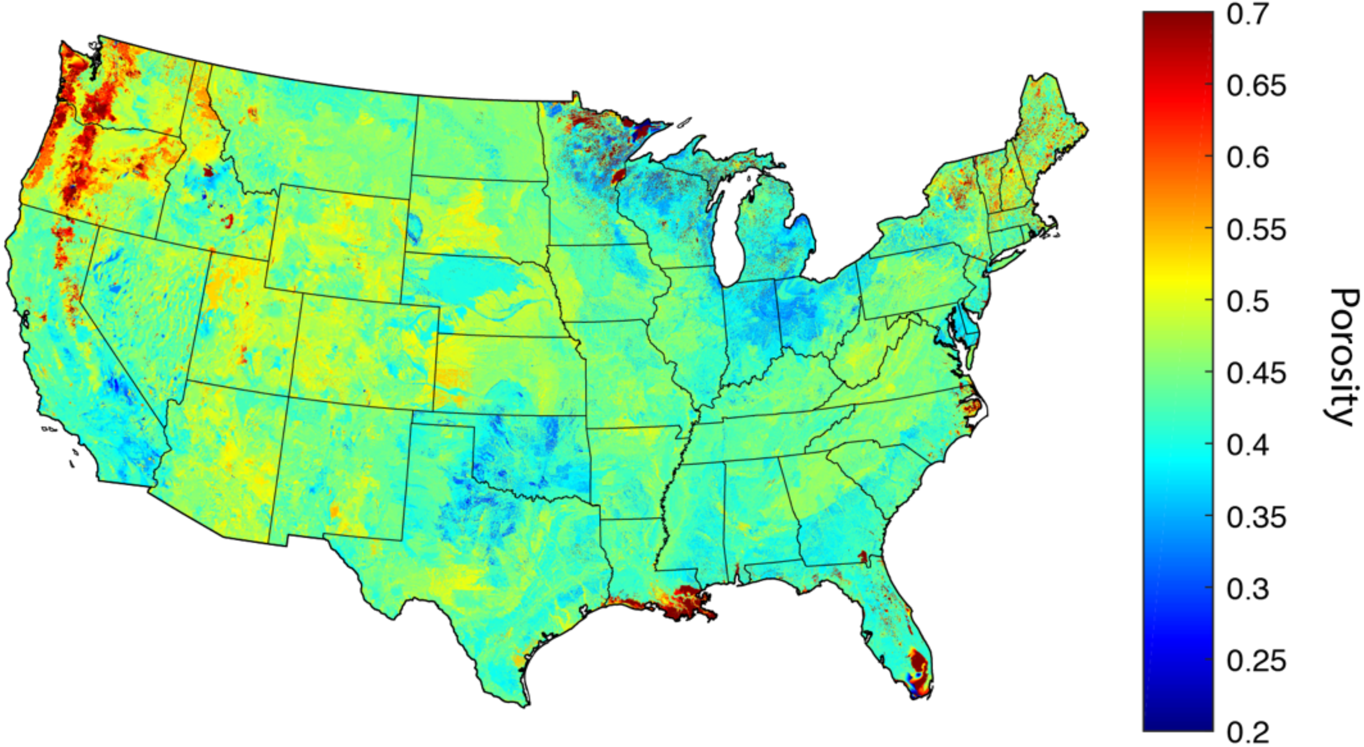
- Clay content obtained from the National Cooperative Soil Survey



NCSS not defined in all areas.

Surficial Porosity

- Gaps filled in based on smooth porosity surfaces fit to porosity values indexed by surface geology.



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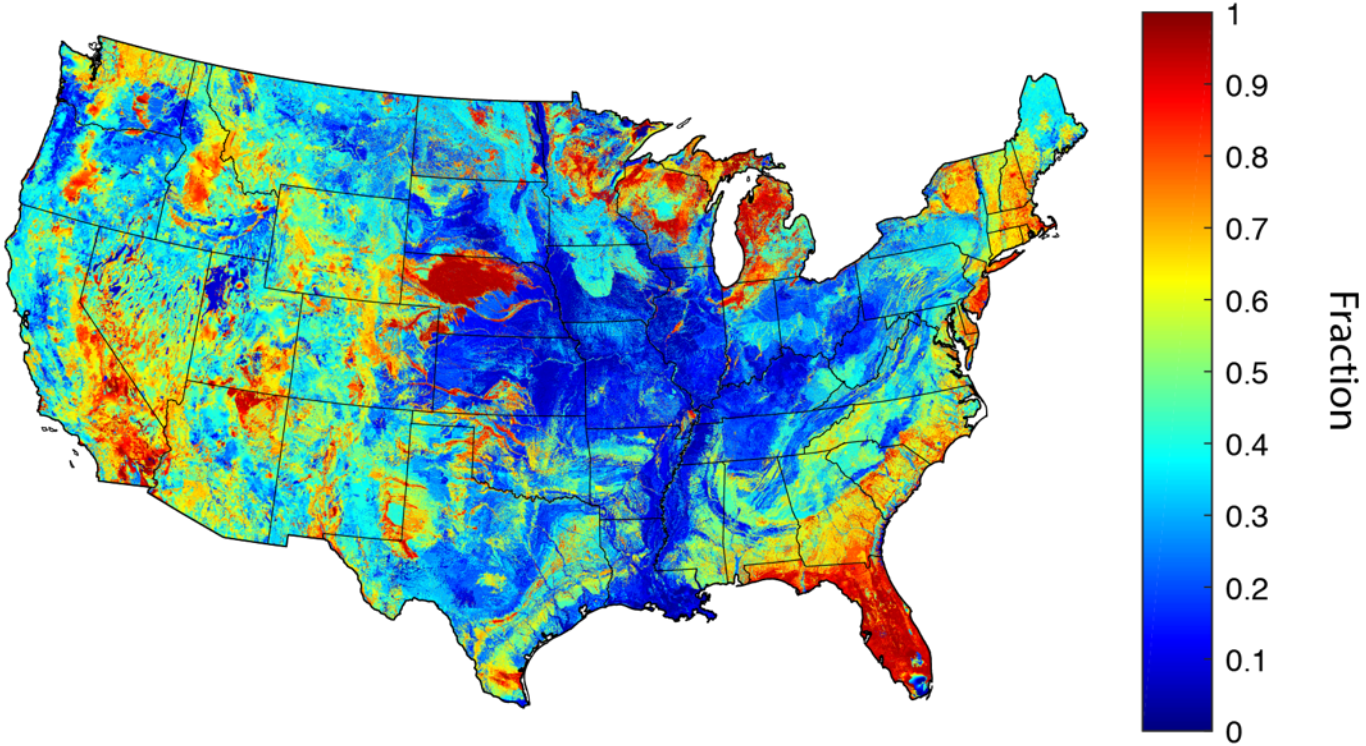
Surficial Sand Fraction

- Gaps filled in based on smooth sand fraction surfaces fit to sand fraction values indexed by surface geology.



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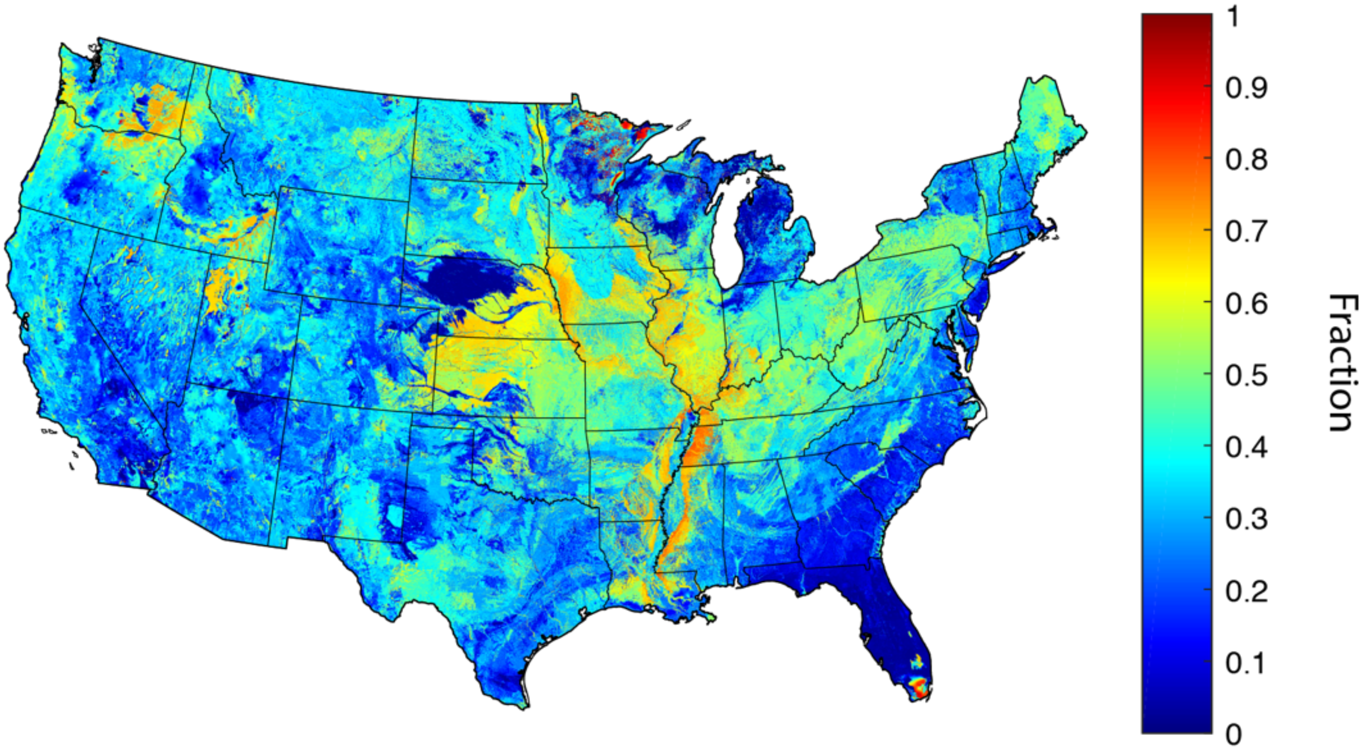
Surficial Silt Fraction

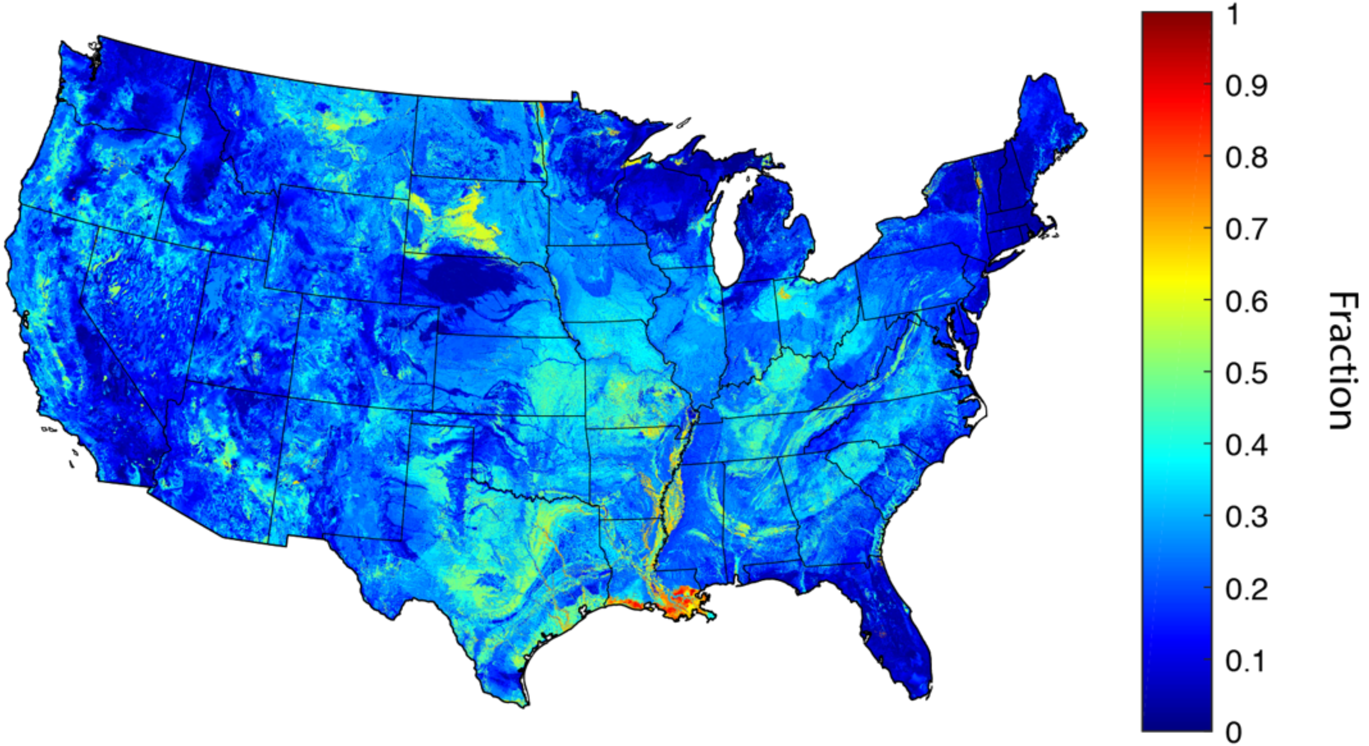
- Gaps filled in based on smooth silt fraction surfaces fit to silt fraction values indexed by surface geology.



NCSS not defined in all areas.

Surficial Clay Fraction

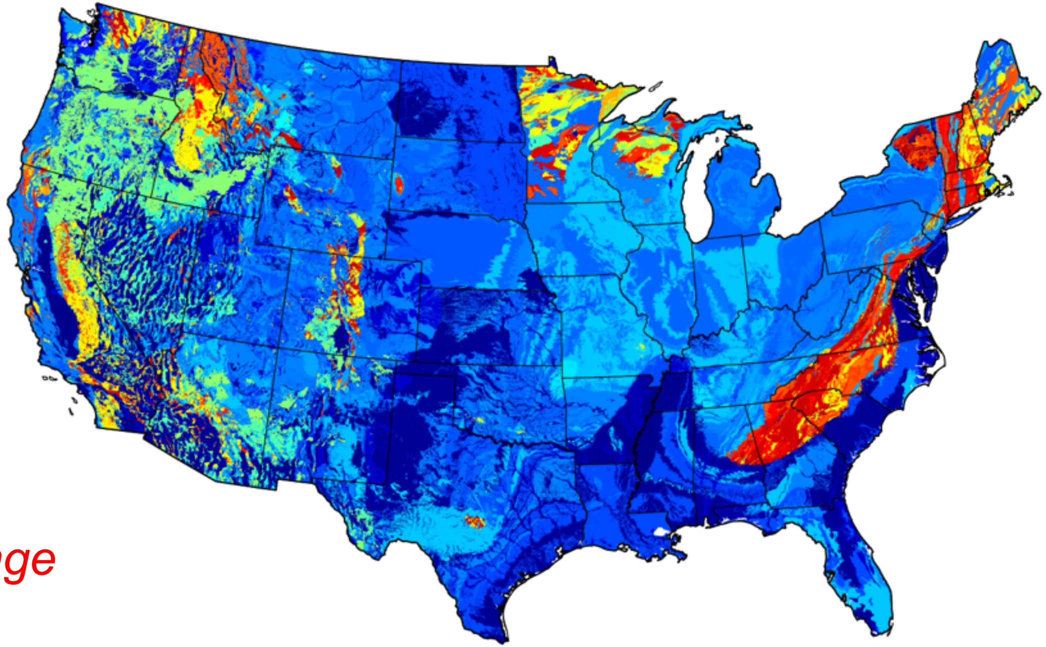
- Gaps filled in based on smooth clay fraction surfaces fit to clay fraction values indexed by surface geology.



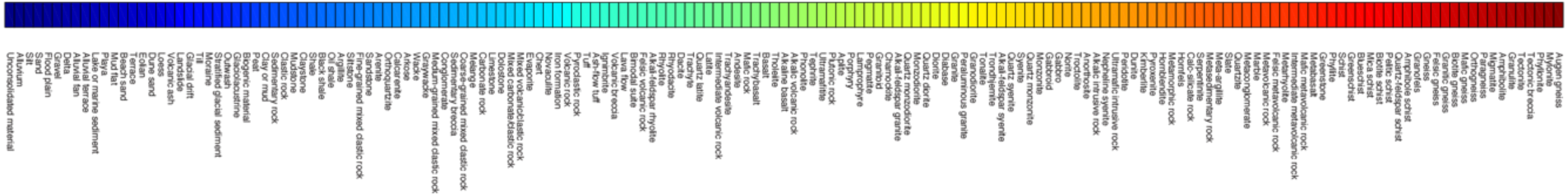
NCSS not defined in all areas.

Surficial Geology

- Rock type obtained from the USGS Mineral resources program on-line spatial database of geologic maps with consistent lithology and age

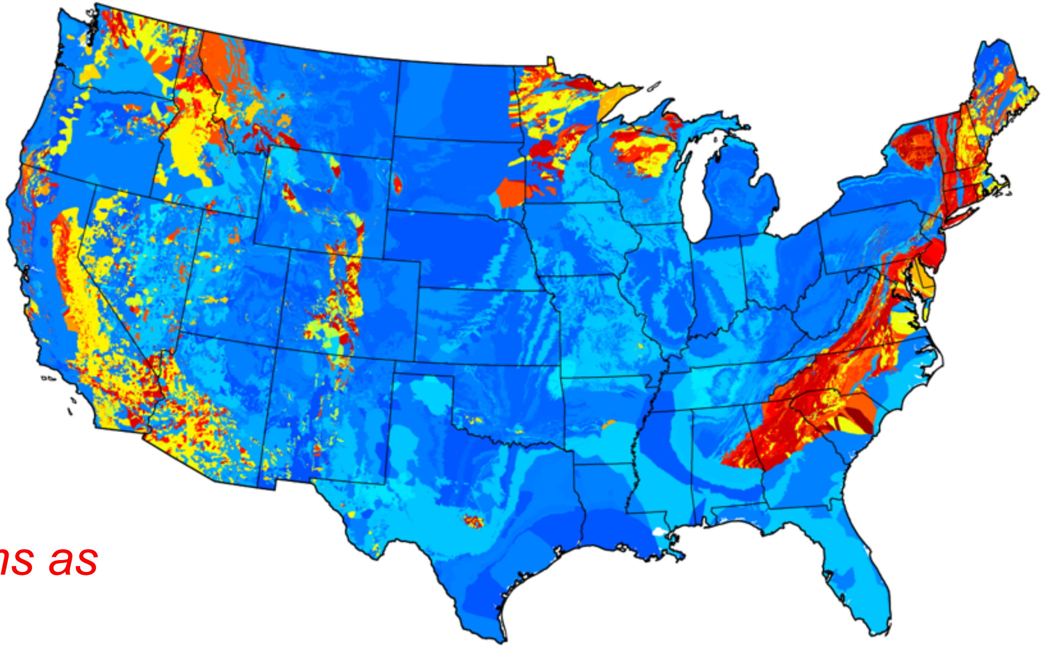


Definitions and Level of detail change across state borders.

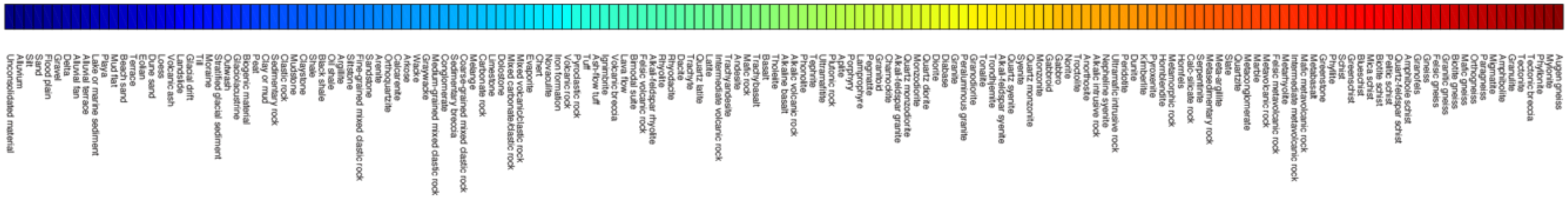


Bedrock Geology

- Bedrock geology map using surface geology maps with unconsolidated sediments removed and nearest neighbor interpolation

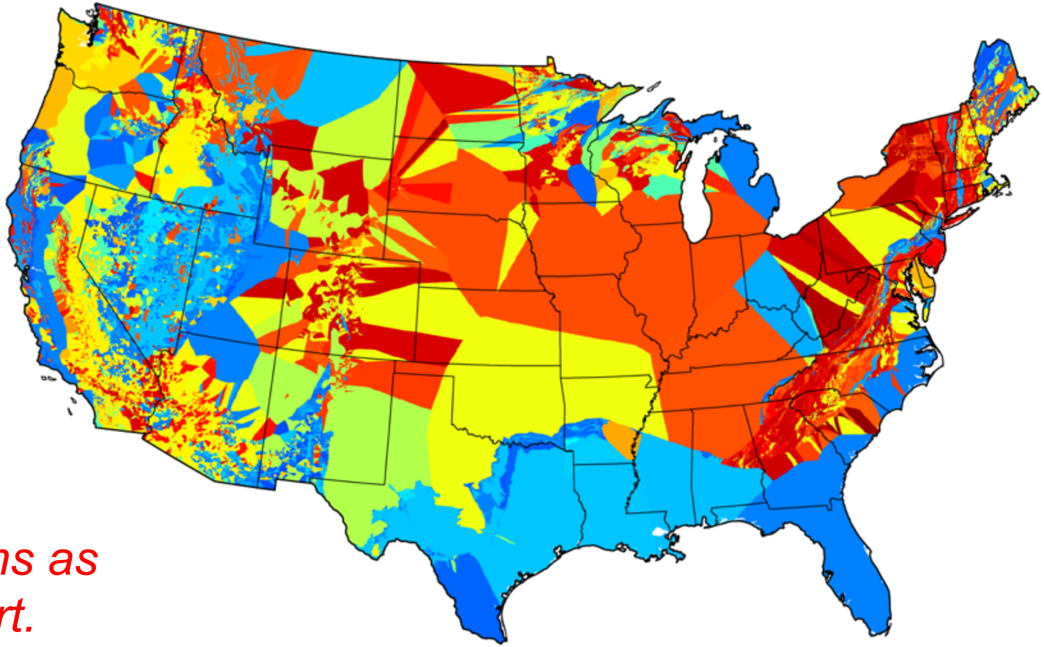


Nearest neighbor will have problems as bedrock outcrops are farther apart.

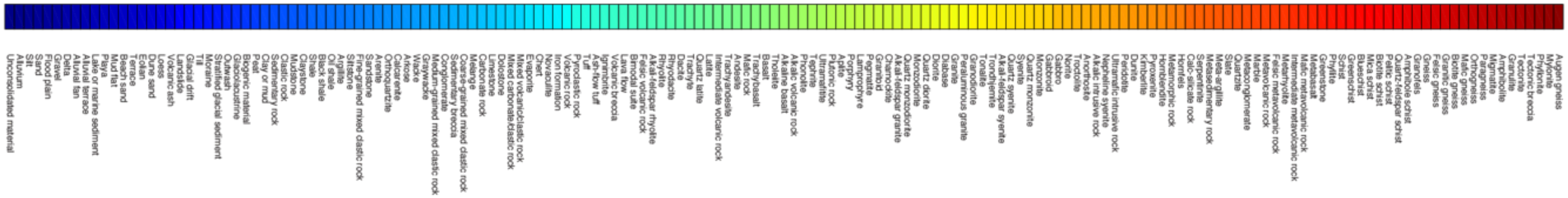


Basement Geology

- Basement geology map using bedrock map with sedimentary rock removed and nearest neighbor interpolation

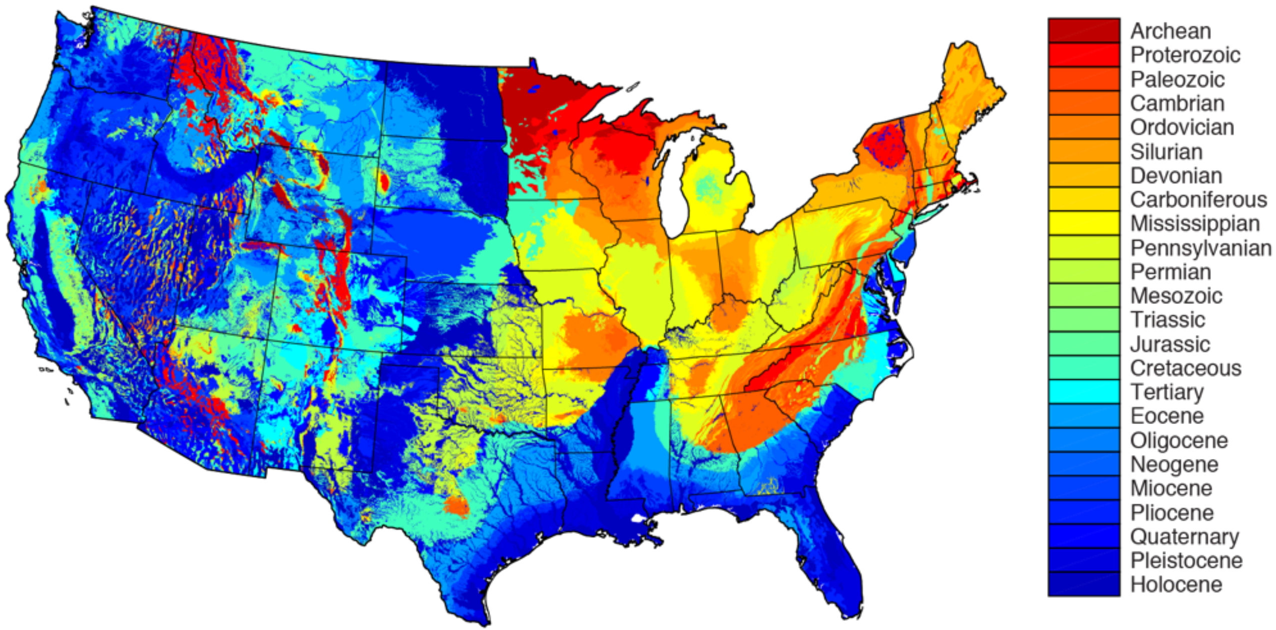


Nearest neighbor will have problems as basement outcrops are farther apart.



Surficial Age

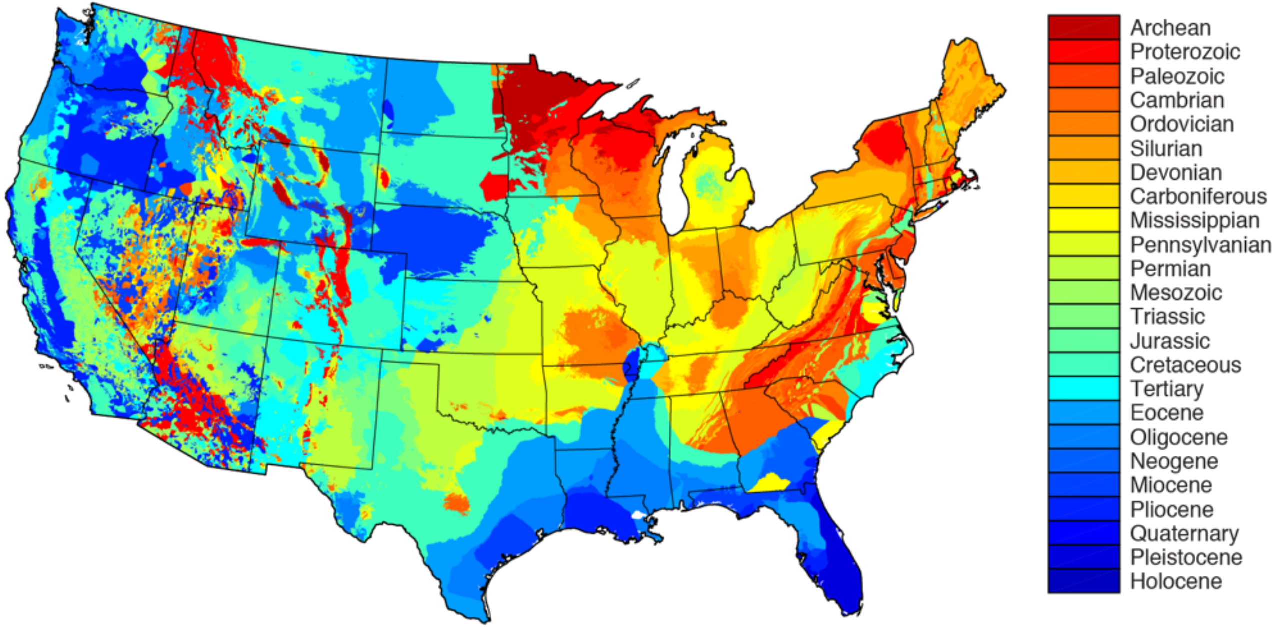
- Age obtained from the USGS Mineral resources program on-line spatial database of geologic maps with consistent lithology and age



Definitions and level of detail change across state borders.

Bedrock Age

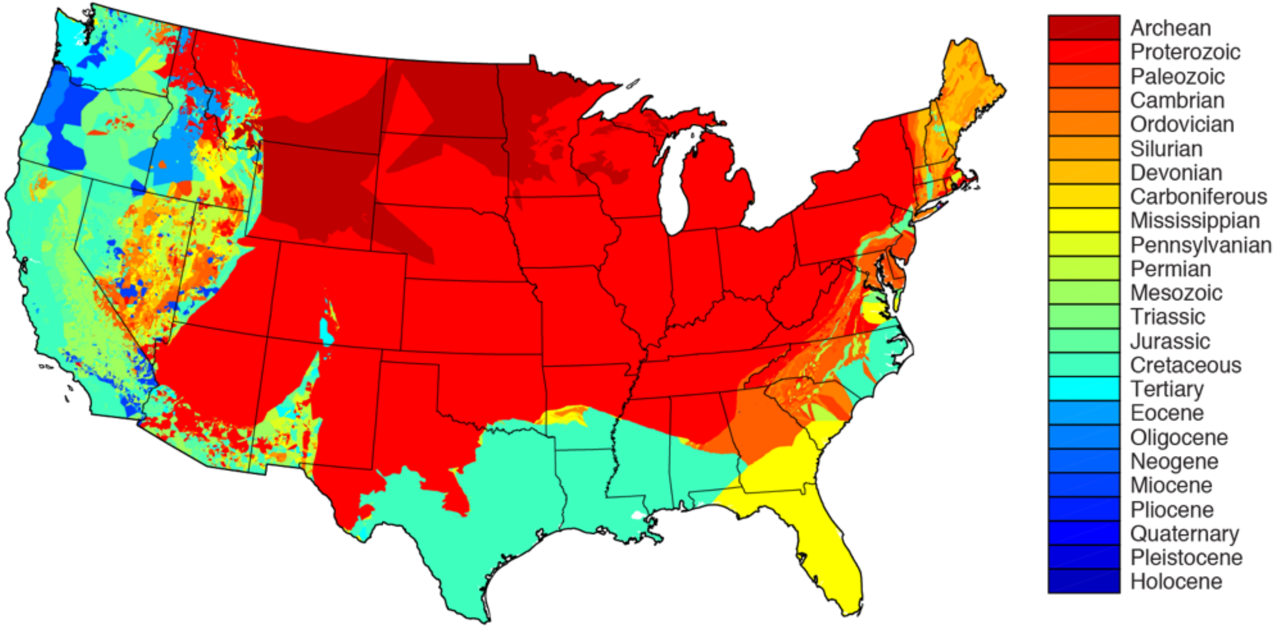
- Bedrock age map using surface age map with unconsolidated sediments removed and nearest neighbor interpolation



Nearest neighbor will have problems as bedrock outcrops are farther apart.

Basement Age

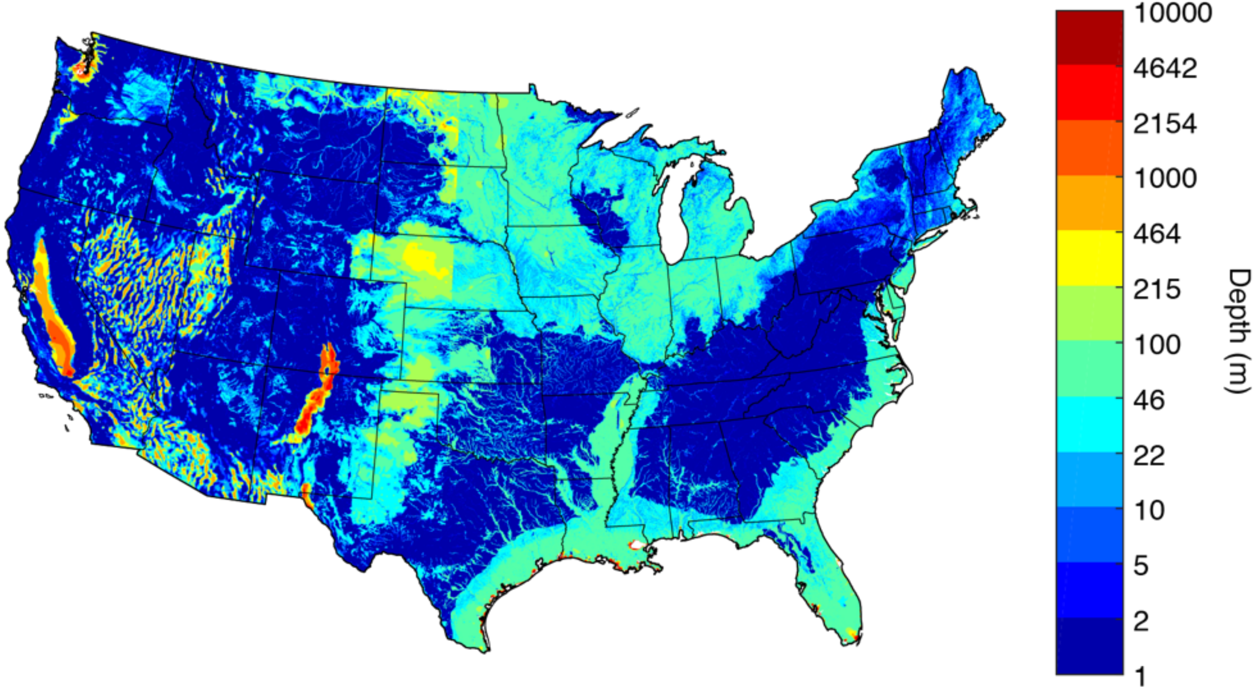
- Basement age map using bedrock age map with bedrock removed and nearest neighbor interpolation



Nearest neighbor will have problems as basement outcrops are farther apart.

Bedrock Depth

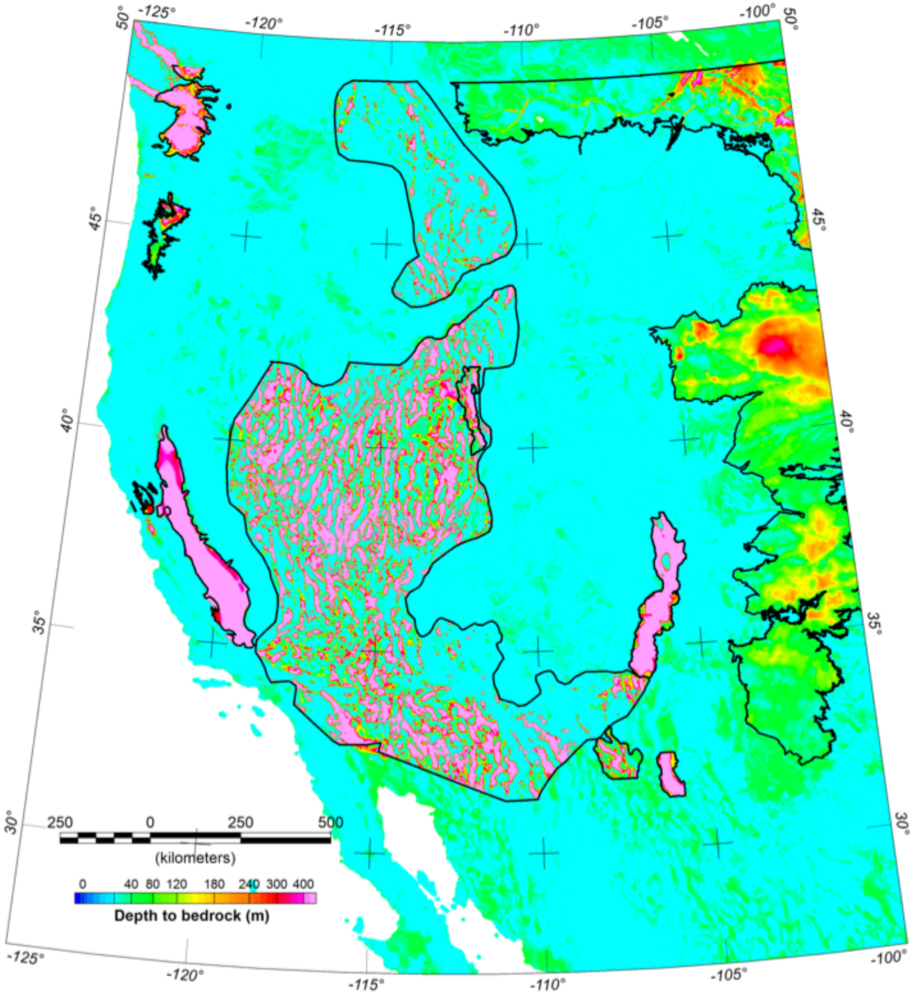
- Depth to bedrock based on modifications to Pelletier and others (2016):
  - modified to account for depths greater than 50 m using a minimum curvature method



Simplified assumptions, max. 50 m depth in EUS, residuum not included.

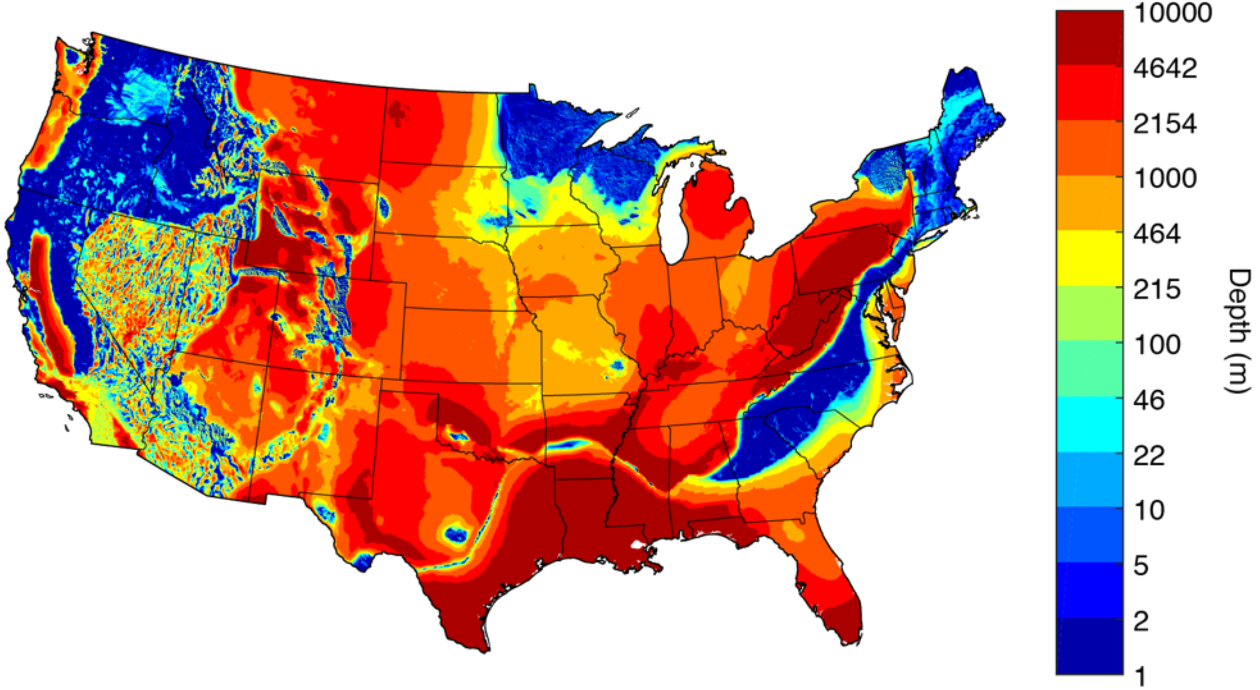
Depth to Bedrock: WUS

Location	Reference	Method
Great Valley, California	Williamson, et al., 1989	Wells
Northern San Francisco Bay, California	Langenheim et al., 2010	Gravity
Portland, Tualitin and Willamette Basins, Oregon	Conlon et al., 2005	Wells
Puget Sound, Washington	Eungard, 2014	Mixed
Salt Lake Valley, Utah	Radkins et al., 1989	Mixed
Basin and Range, Arizona, California, Nevada, and Utah	Saltus et al., 1995	Gravity analysis
Basin and Range, Idaho and Montana	Jachens, TBD	Gravity analysis
Basin and Range, New Mexico	Langenheim, TBD	Gravity analysis
San Luis Basin, Colorado and New Mexico	Keller et al., 1984	Gravity, wells
Mimbres Basin, New Mexico and Texas	Heywood, 2002	Wells, gravity
Hueco Bolson, New Mexico and Texas	Heywood and Yager, 2002	Wells, gravity
Albuquerque Basin, New Mexico	Grauch and Connell, 2002	Gravity
Glacial deposits east of the Rockies: Montana, North Dakota, South Dakota	Soller et al., 2013	Mixed
The high plains sediments: Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas	Gutentag, 1984; Cedarstrand, 1998; Houston et al., 2013	Mixed
Offshore areas in San Francisco Bay, the Columbia River, and Puget Sound	Whittaker et al., 2013	Mixed



Basement Depth

- Depth to basement based on improvements to Mooney and Kaban (2010). Improvements include, for example, gravity-based surveys in the western United States and Depth to Precambrian basement in the CEUS from Marshak et al. (2017).



Variable definition of basement.

Details: Theory

Theoretical Foundation

To model velocity and density of a porous material as a function of depth, we rely on Biot-Gassmann theory as presented by Lee (2010). The P-wave and S-wave velocity, V_p and V_s, of the composite material, denoted by subscript b, is

$$V_p = \sqrt{\frac{k_b + 4\mu_b/3}{\rho_b}} \qquad V_s = \sqrt{\frac{\mu_b}{\rho_b}}$$

and are functions of density, ρ_b, and bulk and shear moduli, k_b and μ_b. The moduli are functions of the solid bulk and shear moduli, K_s and μ_s, the average moduli, K_{av}, and the Biot coefficients, β_p and β_s,

$$k = K_s\left(1-\beta_p\right) + \beta_p^2 K_{av} \qquad \mu = \mu_s\left(1-\beta_s\right).$$

The average bulk modulus, K_{av}, is a function of porosity, ϕ, and the bulk modulus of water, K_w, and or air, K_a,

$$\frac{1}{K_{av}} = \frac{\beta_p - \phi}{K_s} + \frac{\phi}{K_{w,a}},$$

and the Biot coefficients are

$$\beta_p = \frac{\phi(1+\alpha)}{1+\alpha\phi} \qquad \beta_s = \frac{\phi(1+\gamma\alpha)}{1+\gamma\alpha\phi}$$

The parameters α and γ control the sensitivity of the Biot coefficients to porosity, where γ is given by

$$\gamma = \frac{1+m\alpha}{1+\alpha},$$

and m and α are functions of differential pressure (see calibration section).

Density, below the water table, is simply

$$\rho_b = \rho_s\left(1-\phi\right) + \rho_w\phi.$$

Based on in-situ and laboratory data, we assume that porosity increases with depth according to

$$\phi = \phi_0 \exp\left(-ap_N\right)$$

where ϕ_0 is the porosity at zero differential pressure, p_N is the differential pressure normalized by surficial pressure (101 kPa) and a is a constant controlling how quickly porosity decreases with increasing pressure or depth.

The parameters ϕ_0, a, m, and, α are estimated during calibration.

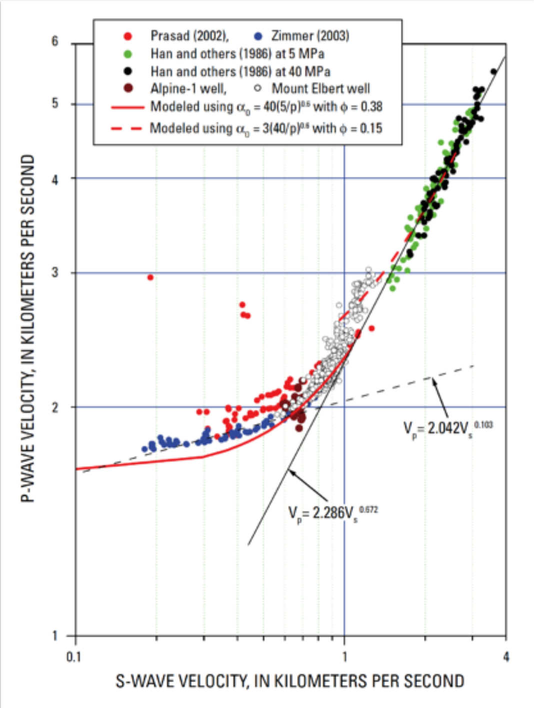
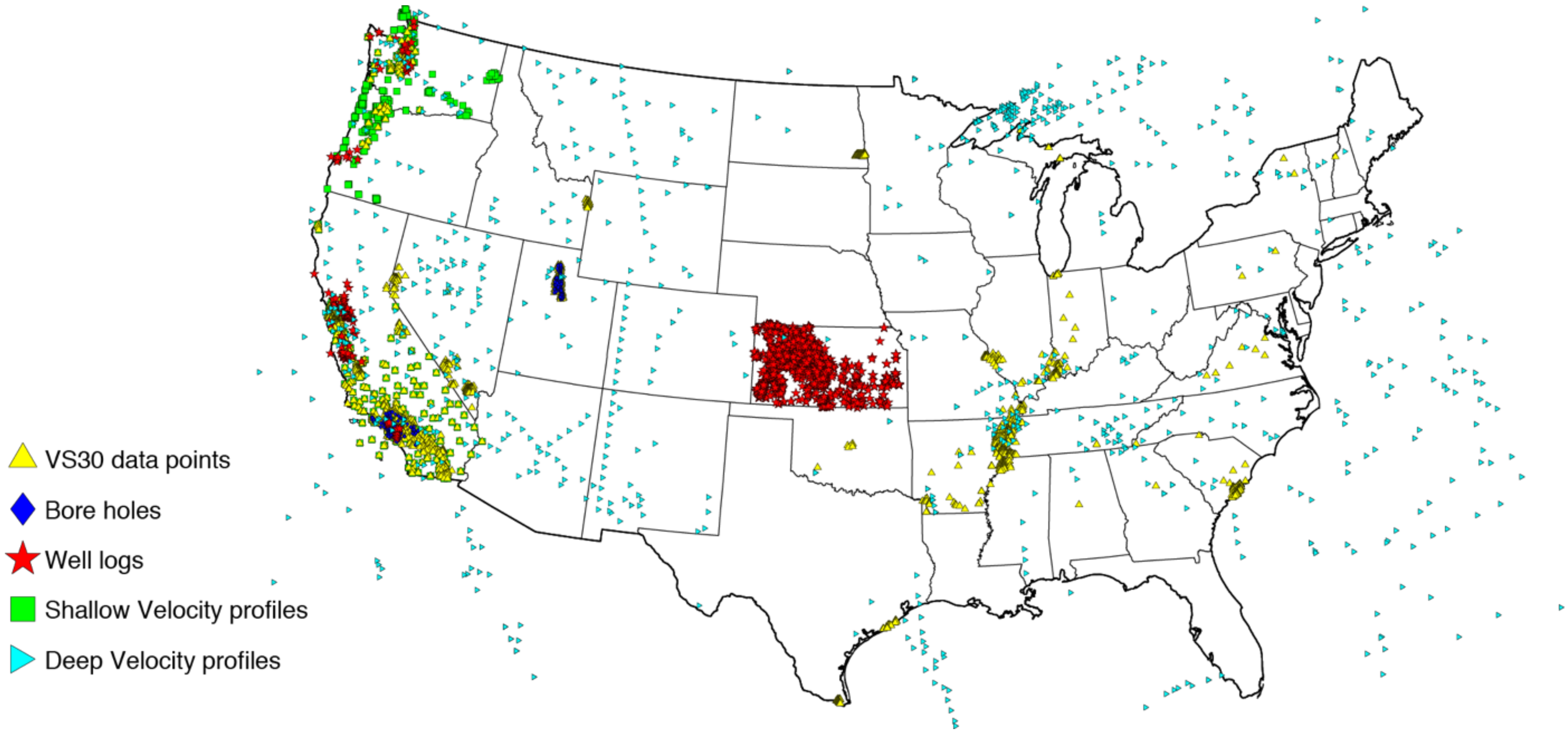


Figure 3 from Lee (2010) showing measured P-wave velocity versus S-wave velocity and the effect of the Biot-Gassmann relation for fully saturated sands.

Details: Calibration

Measured Data and Calibration



Calibration: Well Logs

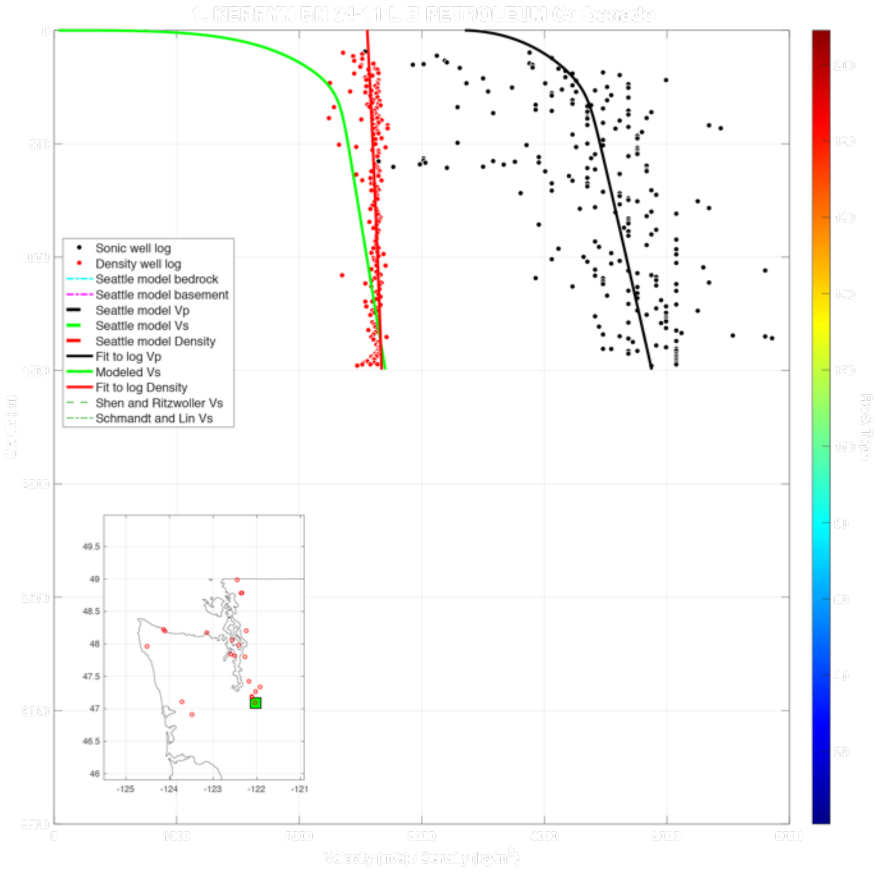
- Define how porosity varies with depth

$$\phi = \phi_0 \exp\left(-a p_N\right)$$

p_N — pressure as a function of depth

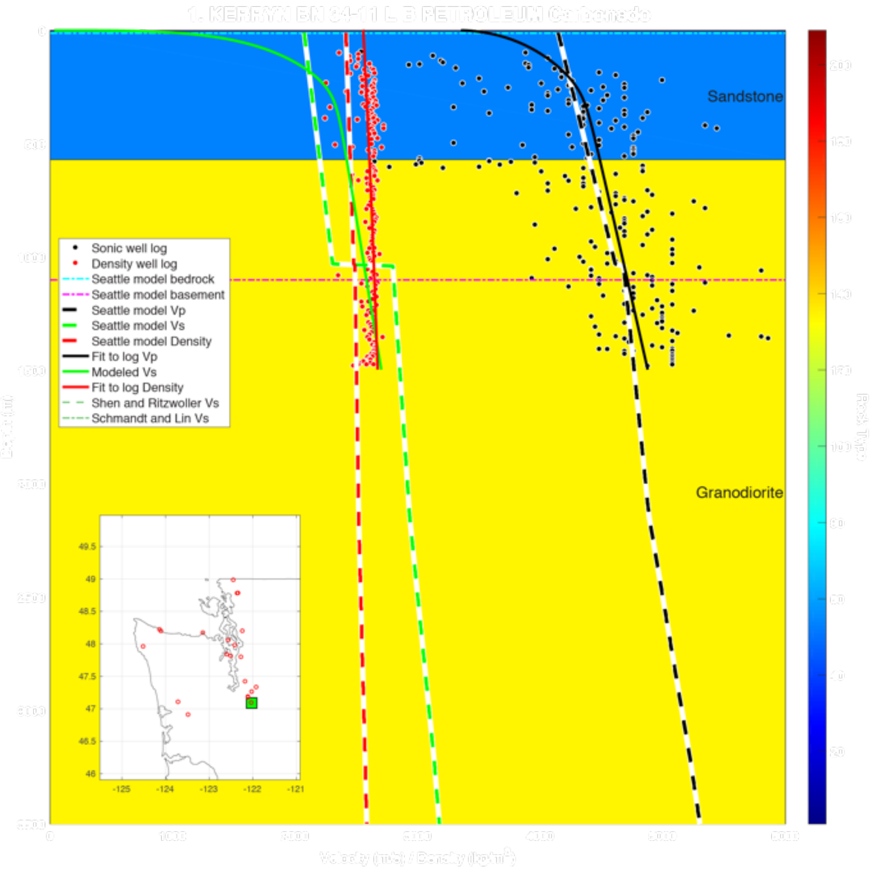
ϕ_0 — porosity at zero pressure

a — parameter controlling how quickly porosity decreases with depth.



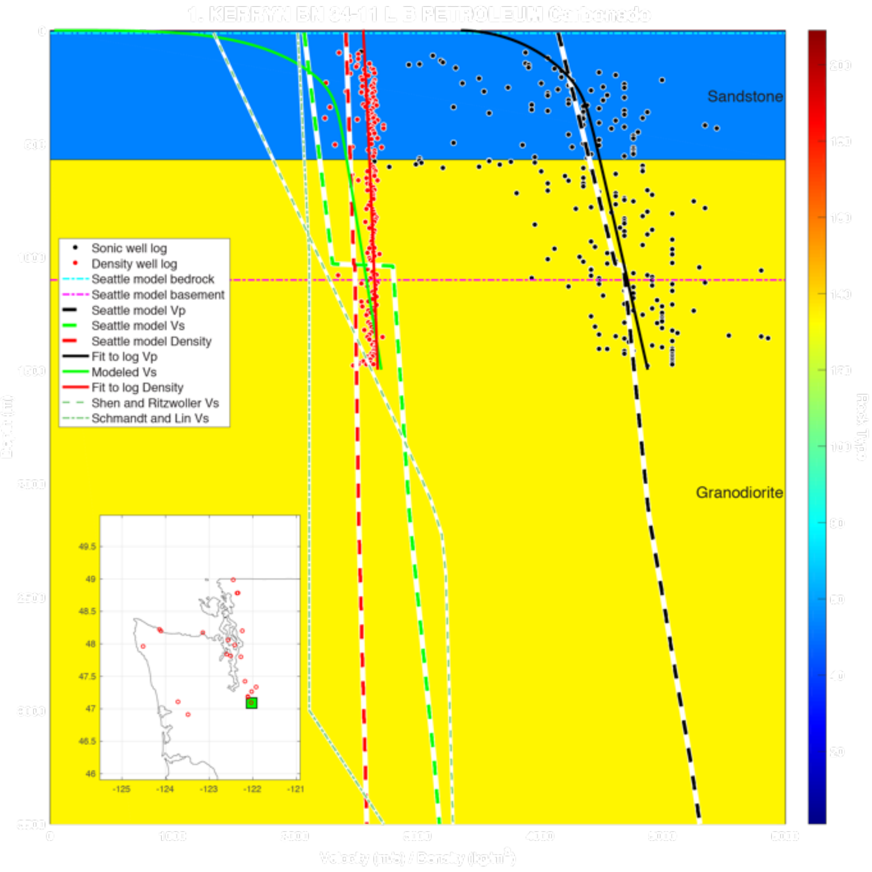
Calibration: Well Logs

- Seattle seismic model
  - Surfaces defining depth to bedrock and basement
  - P-wave velocities increase along linear segments within Quaternary sediments and are defined by tomographic results within tertiary basins.
  - S-wave velocity is assigned by a Vp/Vs ratio that deceases from 2.5 to 2.2 in the unconsolidated sediments and is 2 in bedrock. Density is based on Vp using Brocher's (2008) relations.



Calibration: Well Logs

- Shen and Ritzwoller (2016) and Schmandt and Lin (2015) show similar shear wave velocities but are less sensitive in the near surface.



Next Steps

Next Steps

- Western US (for 2020 NSHM)
  - Complete calibration
  - Validation
    - Using the NGA-West 2 dataset
    - Modeling ground motion time series
  - Estimate uncertainty
- Gather additional data for CEUS
  - Calibrate, Validate, and Apply

Improvements

Improvements

- **Depth to bedrock**
  - Incorporate gSSURGO Root Zone and minimum bedrock depths as minimum constraints.
  - Include Pelletier and others (2016) regolith model.
  - Use IHS well logs for Quaternary horizons.
  - Obtain additional state maps and well logs, for example from the USGS National Water Information System.

Improvements

- **Depth to basement**
  - Implement additional gravity surveys throughout the US.
  - Incorporate IHS well logs as minimum depth constraint.
  - Coordinate with Brudzinski’s NSF basement mapping project for CEUS.

Improvements

- **Surface model**
  - Obtain or derive better surficial porosity model (e.g. Michael E. Wieczorek with USGS Water Resources).
  - Obtain or develop more detailed and consistent surficial geology map, particularly for the CEUS.

Improvements

- **Subsurface geology models**
  - Obtain bedrock and basement geology maps where available.
  - Obtain and implement locally constructed 3D geology models (e.g. for southern California).
  - Coordinate with the National Cooperative Geologic Mapping Program and their vision to produce a 3D geologic model for the Nation.

Improvements

- **Velocity models/modeling**
  - Improved understanding of how porosity and velocity change with depth for a given geology.
  - Consider incorporating aspects of locally constructed velocity models (e.g. those for Seattle, San Francisco Bay Area, Los Angeles, Salt Lake City).

Improvements

- **Velocity models/modeling**
  - Perform tomographic inversion with NCM as starting model to better capture spatial variability in geophysical parameters.

Improvements

- **Additional calibration**
  - Calibration using Love and Raleigh wave dispersion curves from broadband stations.
  - Calibration using additional V_{S30} and well log data.

Improvements

- **Validation**
  - Reduce the variance of intra-event ground motion residuals relative to default values using the NGA-West2 database and ground motion prediction equations.
  - Reproduce long-period waveforms and phase arrival times with 3D simulations of western U.S. earthquakes.