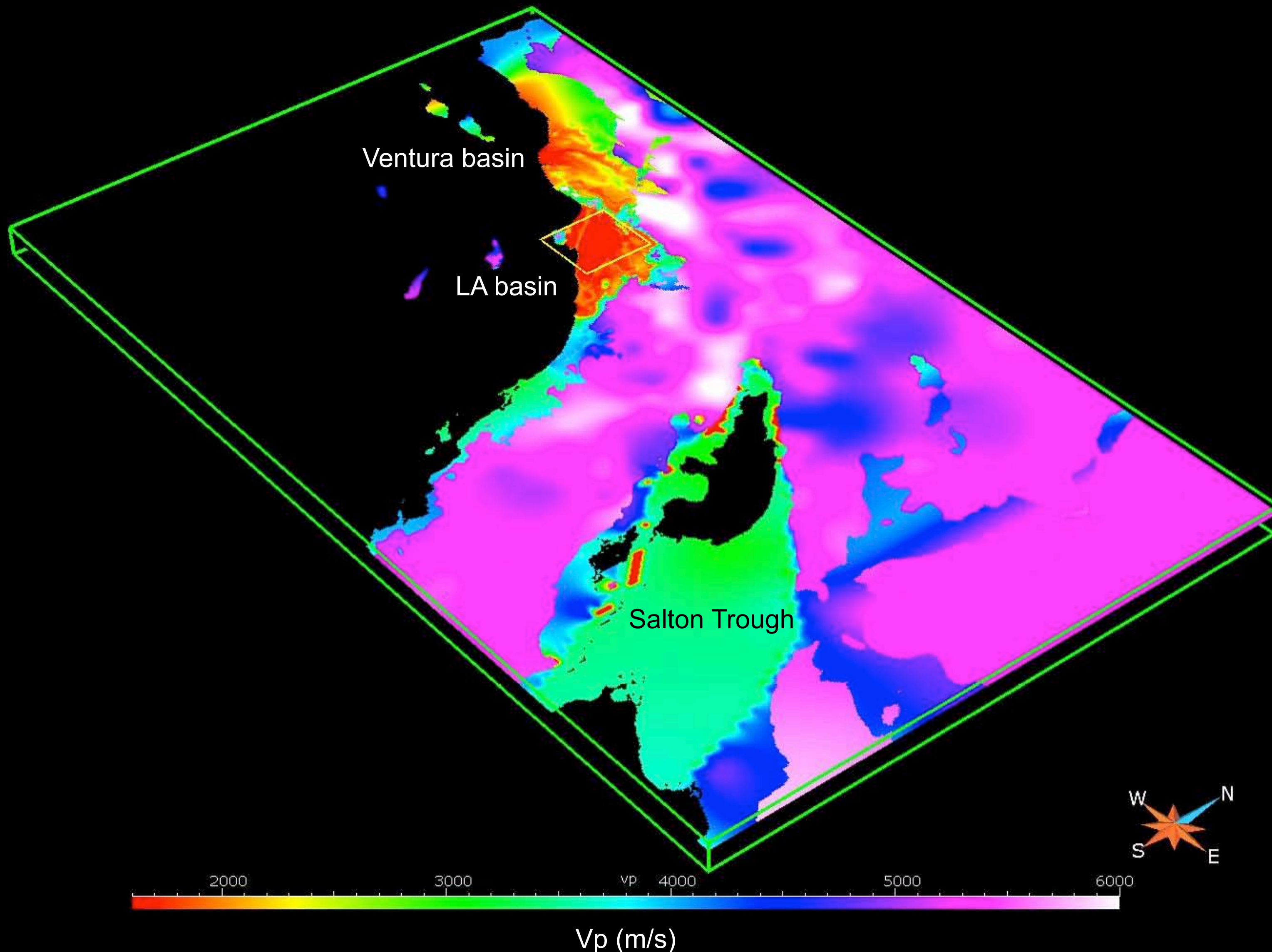
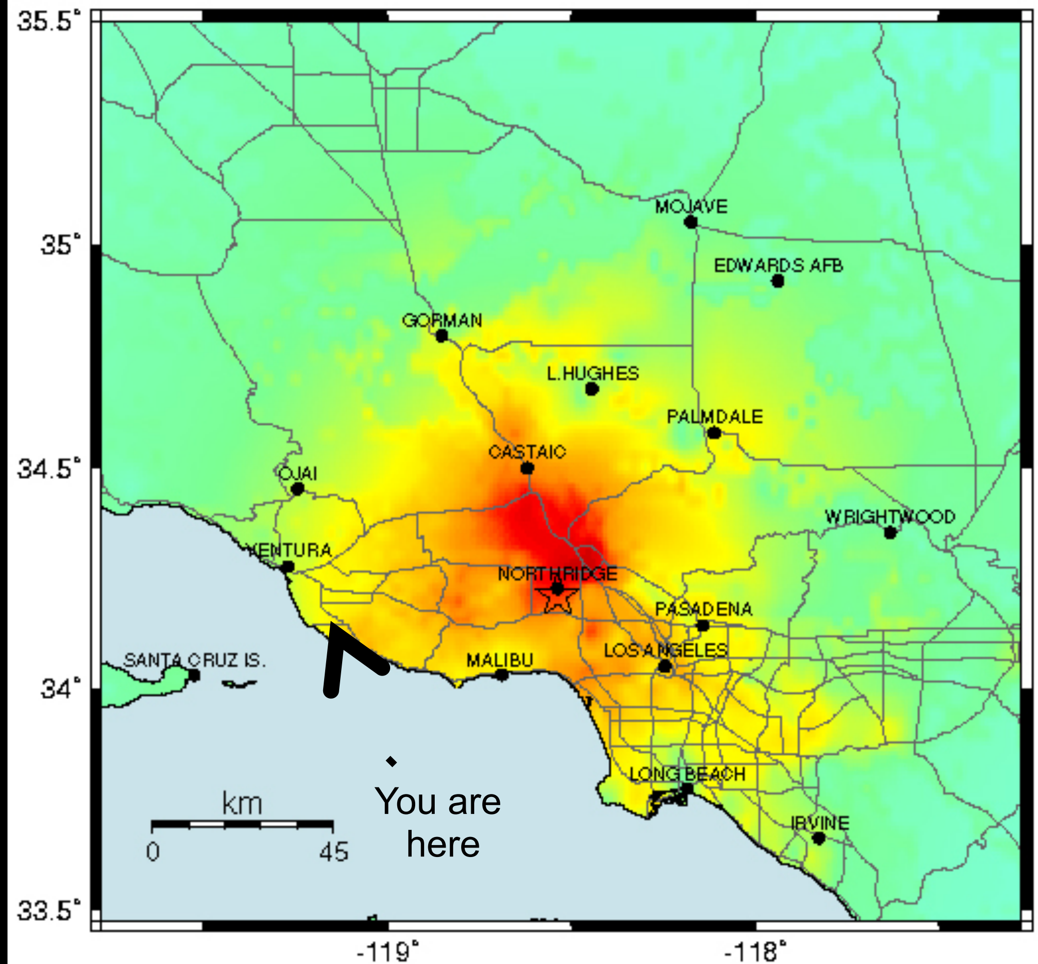
Unified Structural Representation (USR) of the Southern California Crust and Upper Mantle



3D velocity structure has a primary control on the intensity and distribution of hazardous ground shaking

- Rupture nucleation & dynamics
- Wave propagation
- Wave guides & focusing
- Wave amplification & resonance

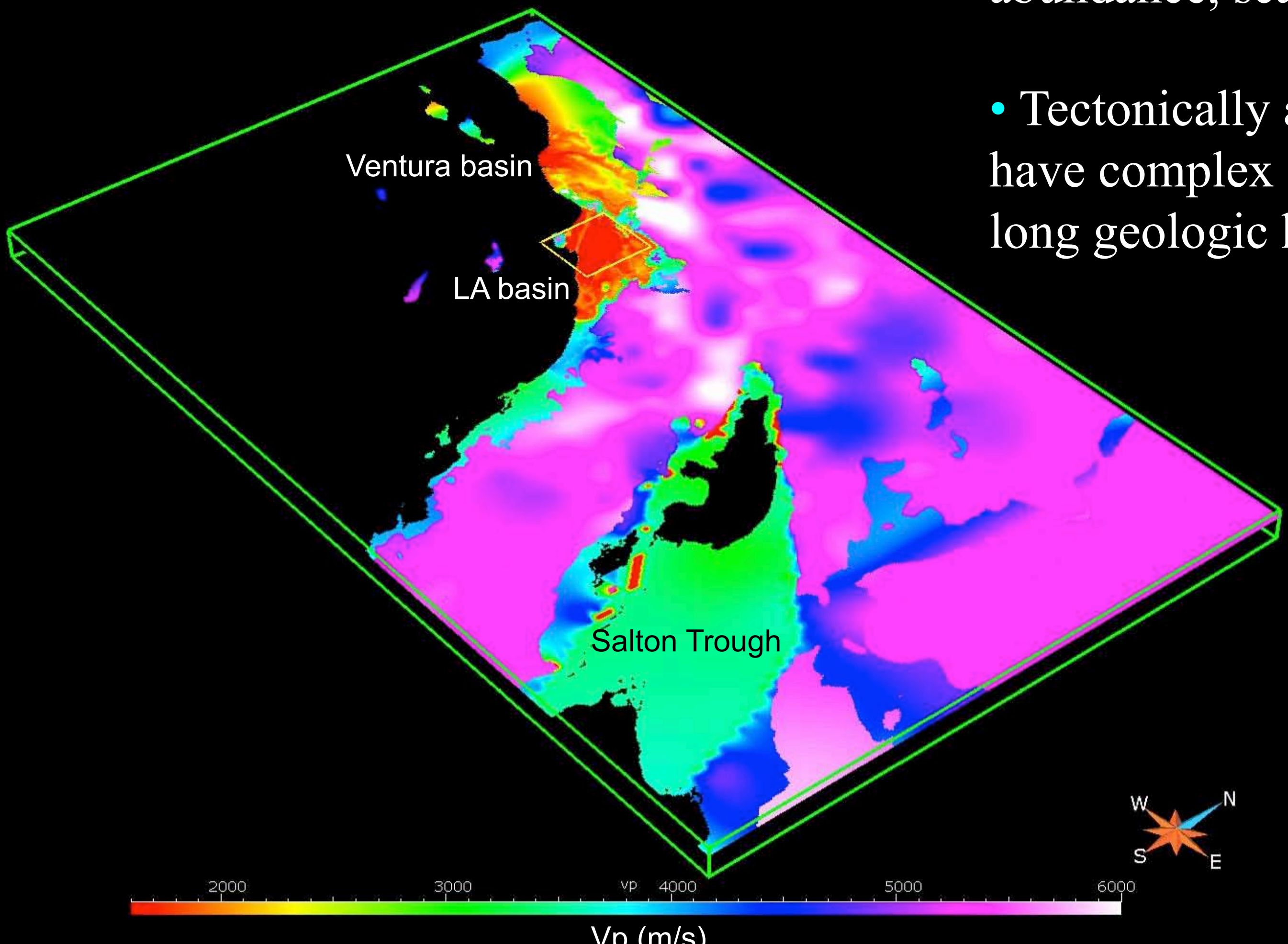
1994 Northridge (M6.7) Earthquake, CA



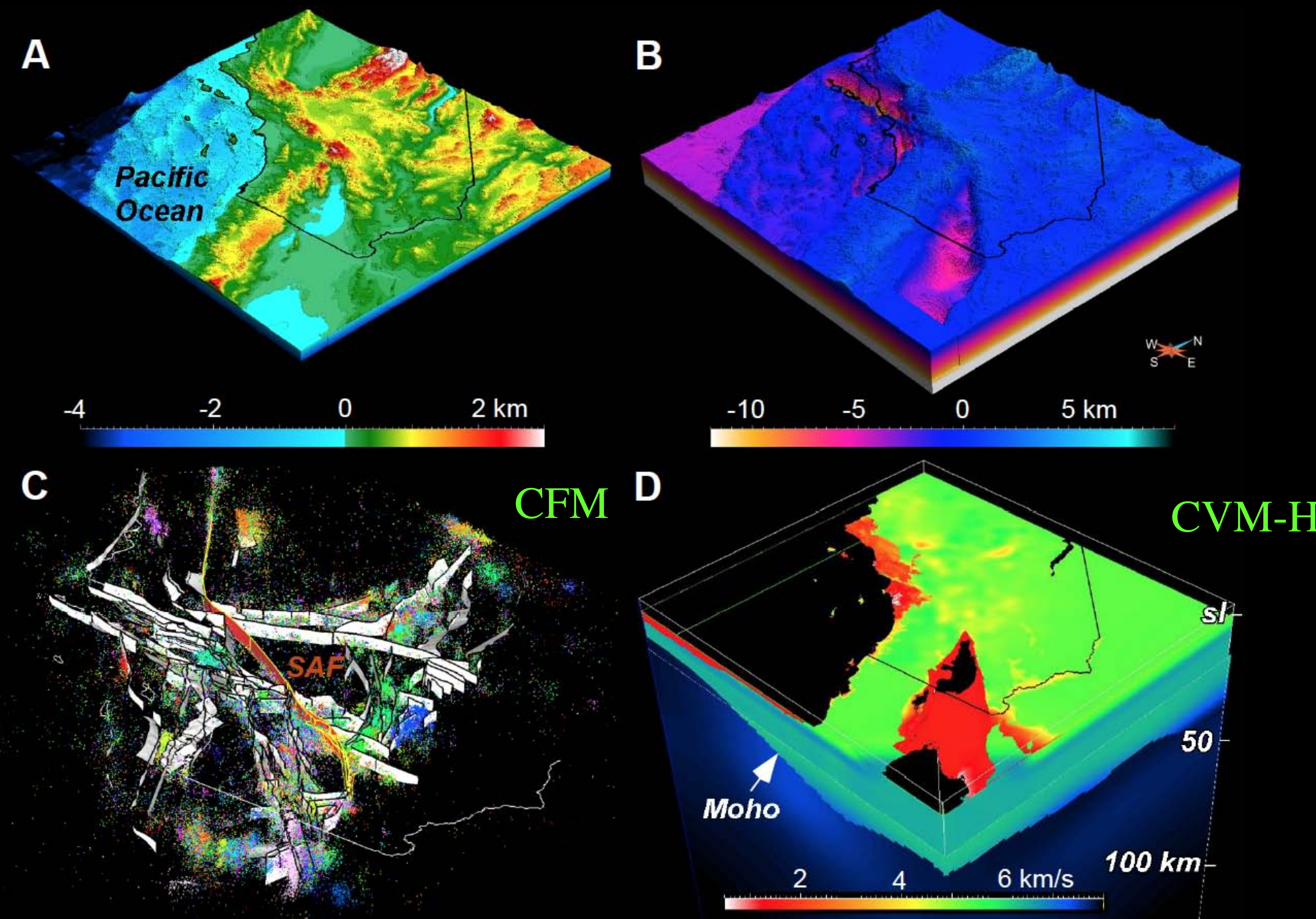
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

3D velocity structures are inherently complex, presenting challenges in their representation

- Velocity structure is heterogeneous over a wide range of scales
- Velocity measurements vary in type, abundance, scale, and frequency
- Tectonically active regions generally have complex structures that reflect a long geologic history



SCEC Unified Structural Representation (USR)



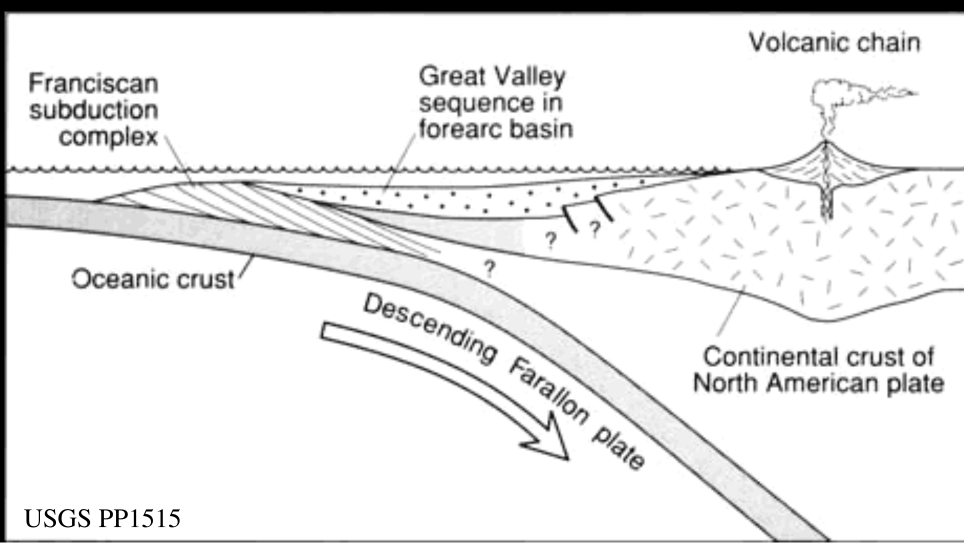
- An object-oriented, 3D description of crust and upper mantle velocity and fault structure in southern California
- The USR development workflow seeks to use the best available data and techniques to constrain velocity structurre, and to ensures internal consistency of model components

California tectonic history

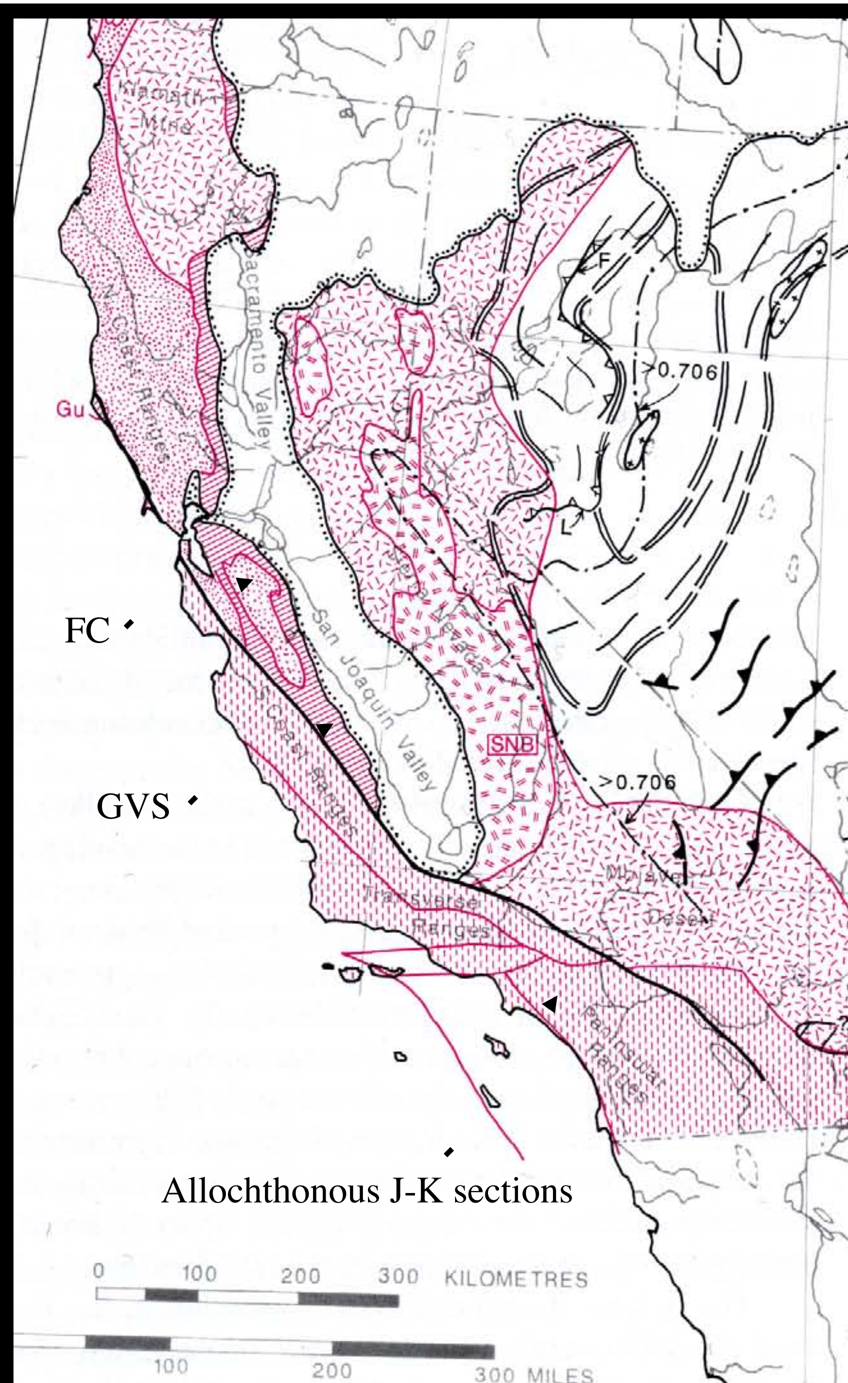
California represents a portion of a much larger, long-lived plate boundary

• convergent plate boundary tectonics originate at least as early as the Carboniferous (Antler Orogeny)

• *"California tectonics"* generally initiated in the Jurassic with accretion of island arc terrains and east directed subduction



USGS PP1515

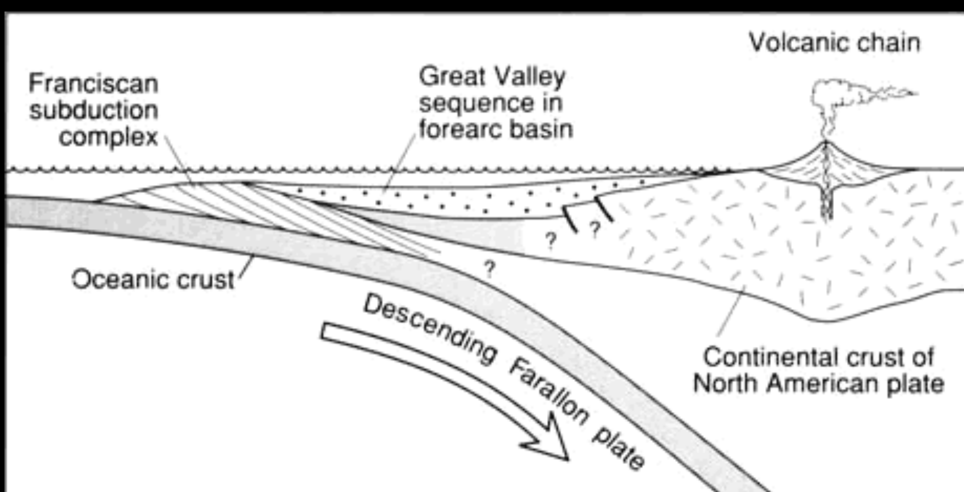


Cowan & Bruhn, (1986)

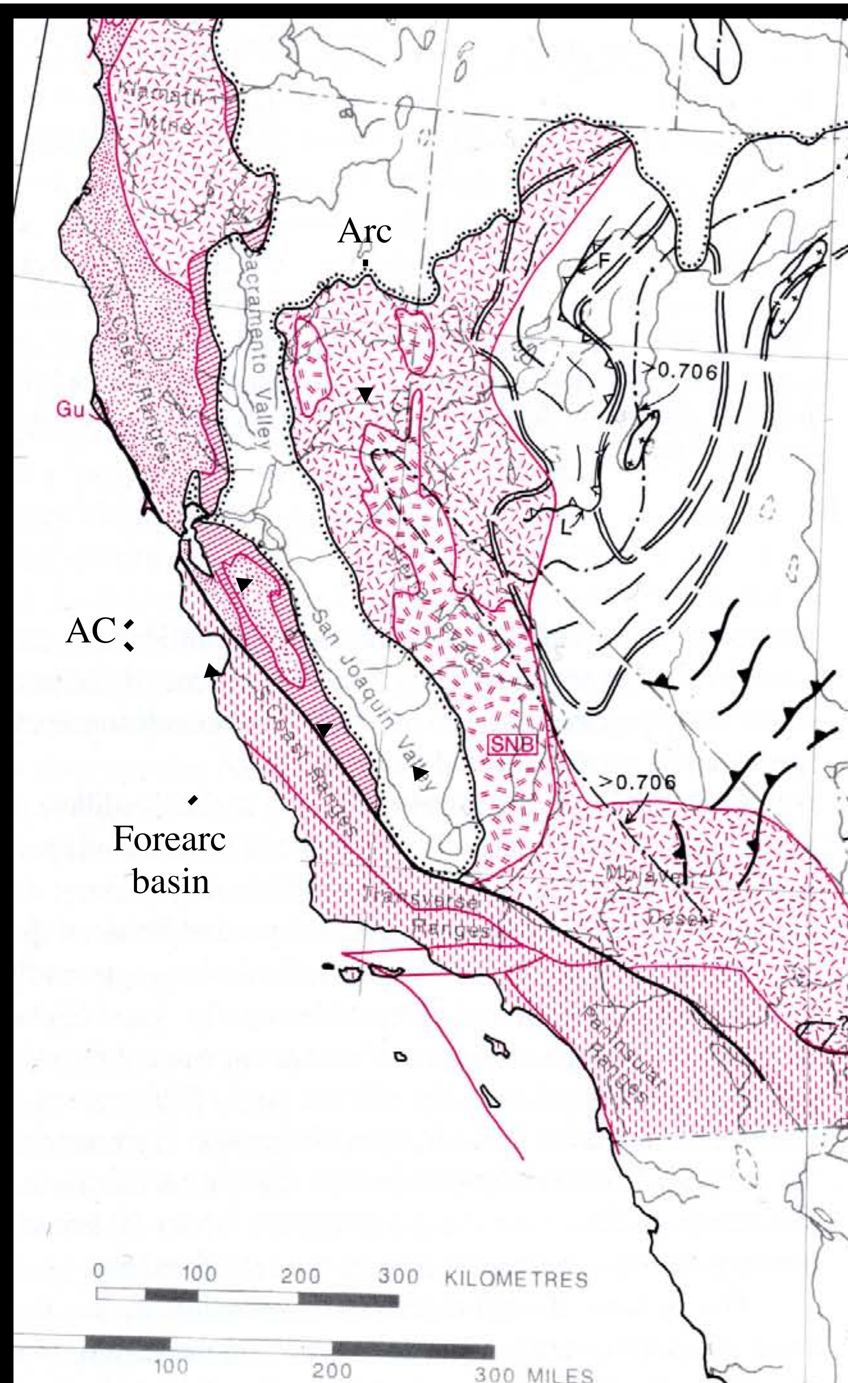
California tectonic history

This history defines the primary “fabric” of California

- **Arc** – Sierra Nevada Block & associated igneous terrains [Jurassic – Cretaceous granitoid rocks]
- **Forearc basin** - Great Valley Sequence [Jurassic – Paleocene forearc basin deposits]
- **Accretionary complex** - Franciscan Complex [Jurassic – Paleocene accretionary prism and oceanic crustal rocks, highP – lowT metamorphism]



USGS PP1515



Cowan & Bruhn, (1986)

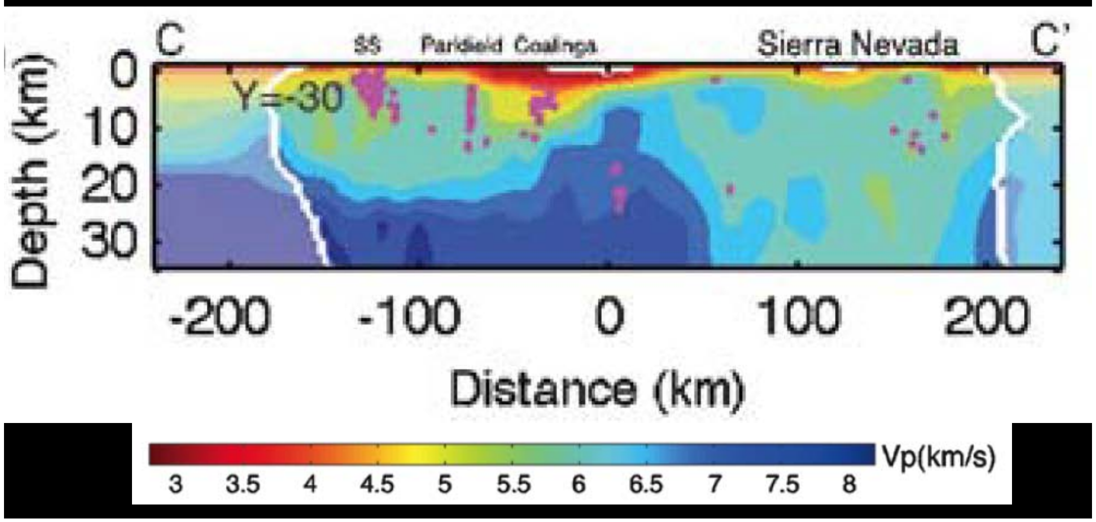
California velocity structure

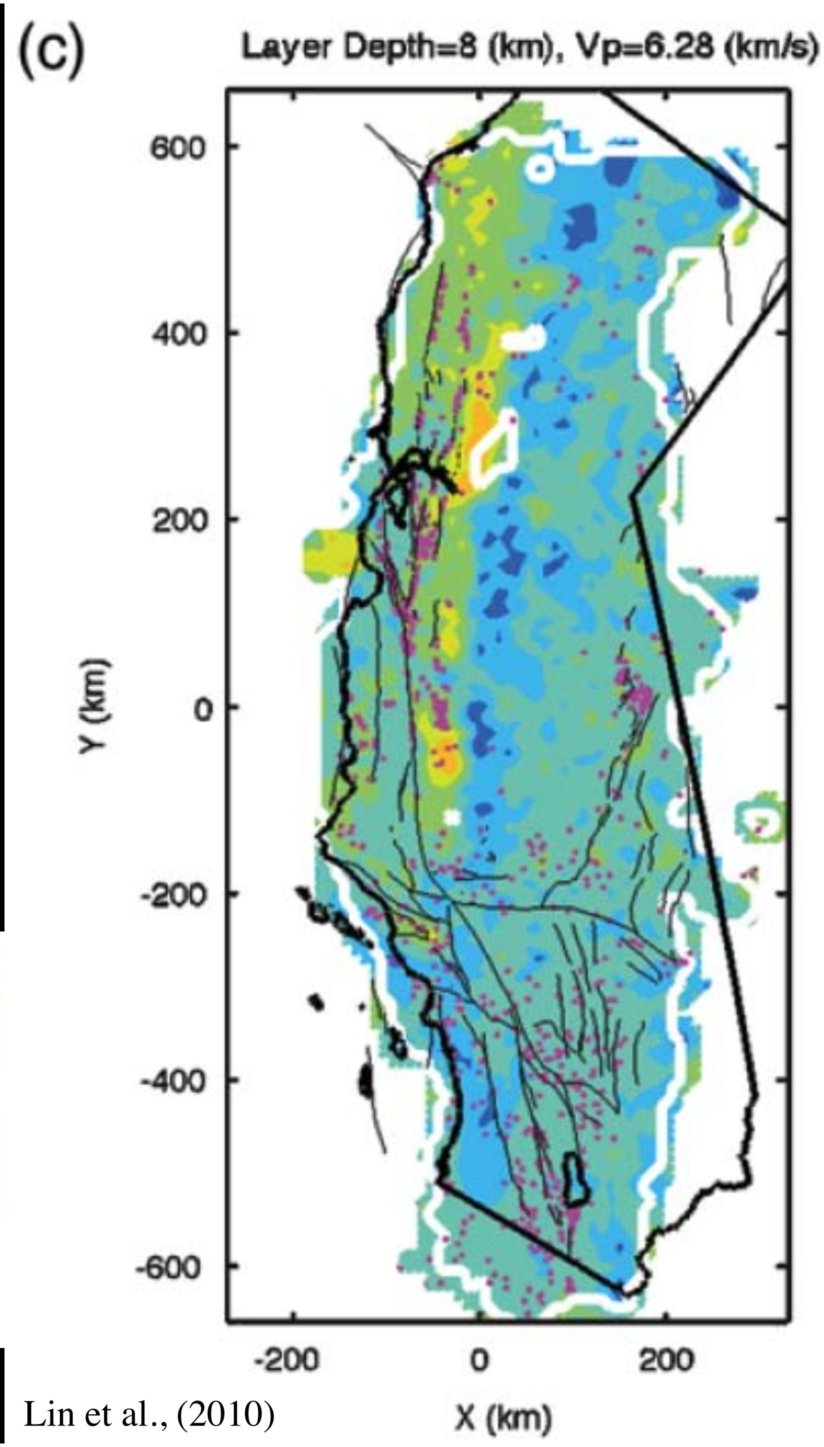
California is characterized by a paired set of high and low velocity regions running through the center of the state.

- High velocity arc

- Low velocity forearc

- High velocity rocks associated with subducted lithosphere





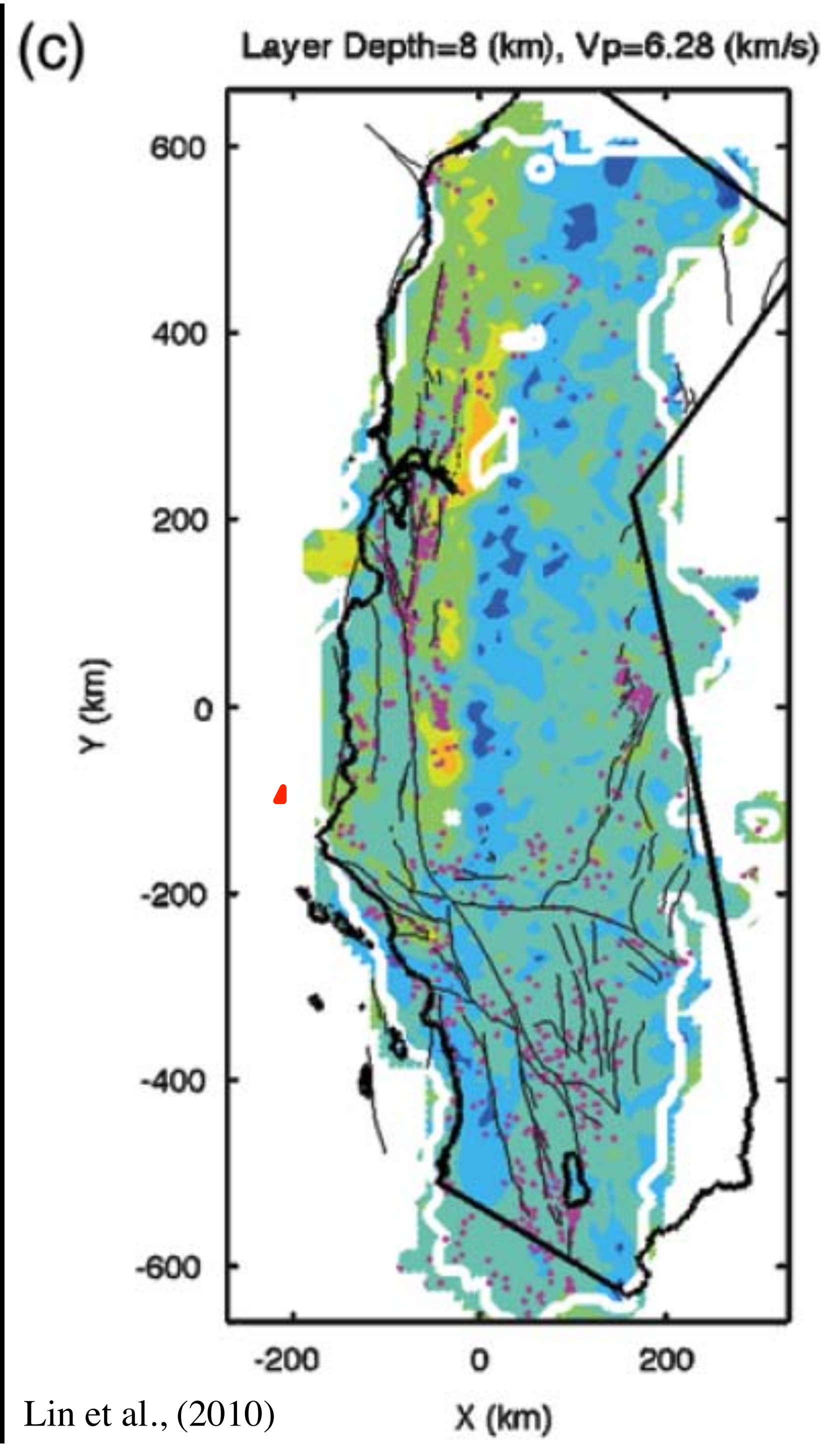
Lin et al., (2010)

California velocity structure

However, this patterns is substantially modified in southern California.

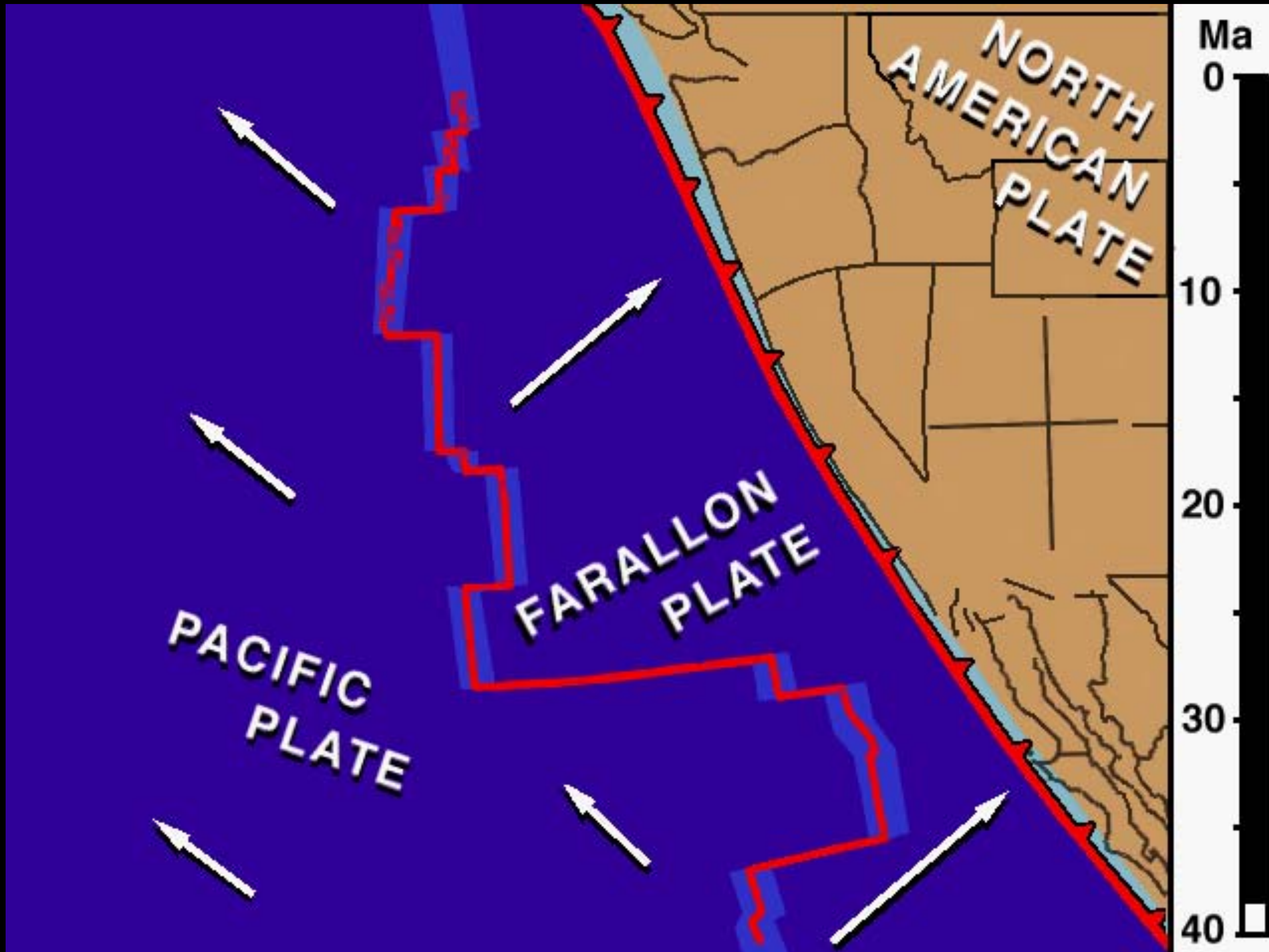
- “Capture” of the Monterey micro plate by Pacific plate motions: rifting and transtension along southern California in the Miocene

- Transition to modern transpressional tectonics in the late Miocene to Pliocene



Lin et al., (2010)

California plate tectonics (Atwater, 2011)



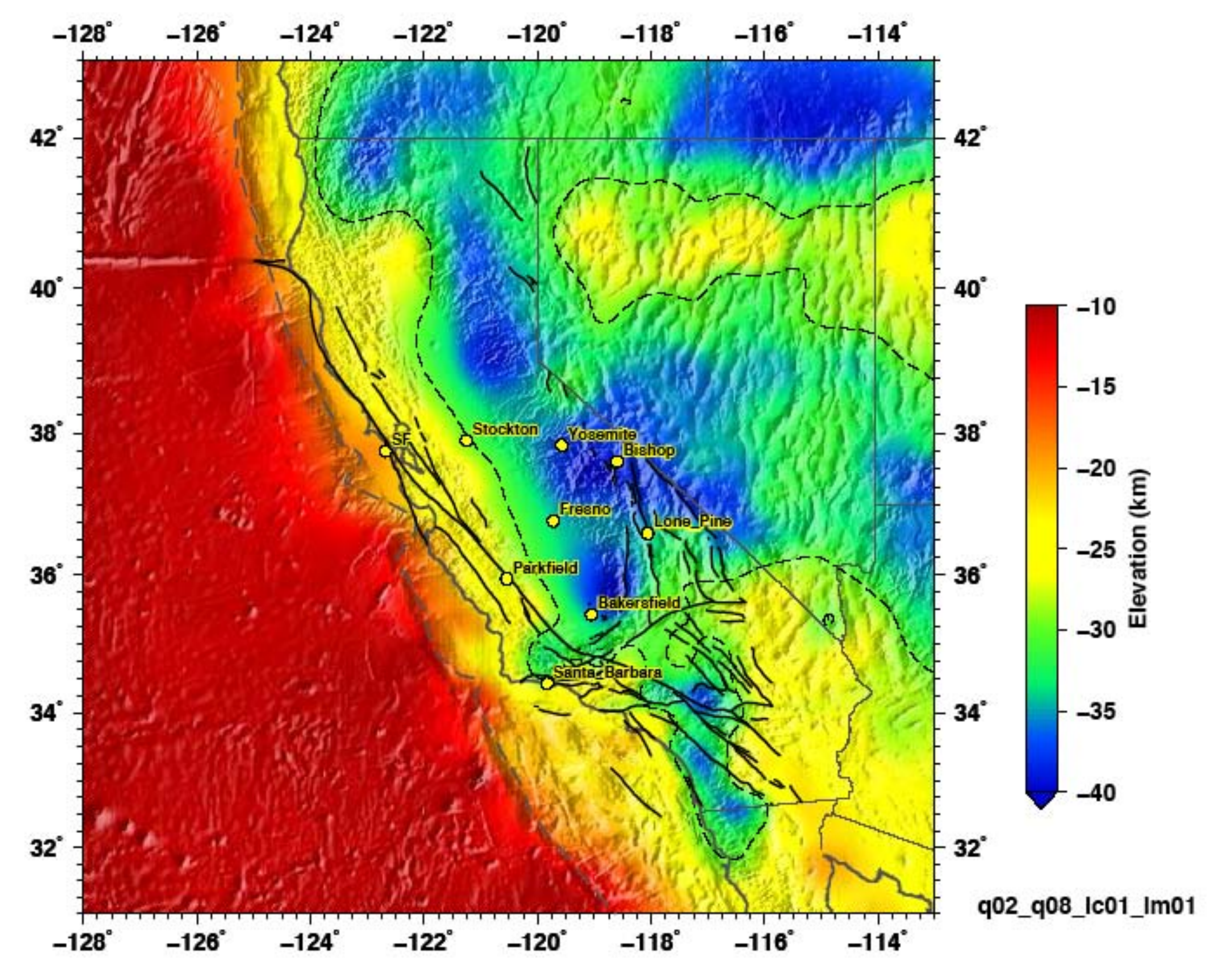
Structure of the California Crust

Depth to the Moho

Crustal thickness

- Continental crust is generally thickest beneath mountain ranges, most of which have felsic igneous sections.

- Crust is generally thinner in areas of crustal extension due to rifting and transform plate tectonics. These areas include many of the major sedimentary basins.

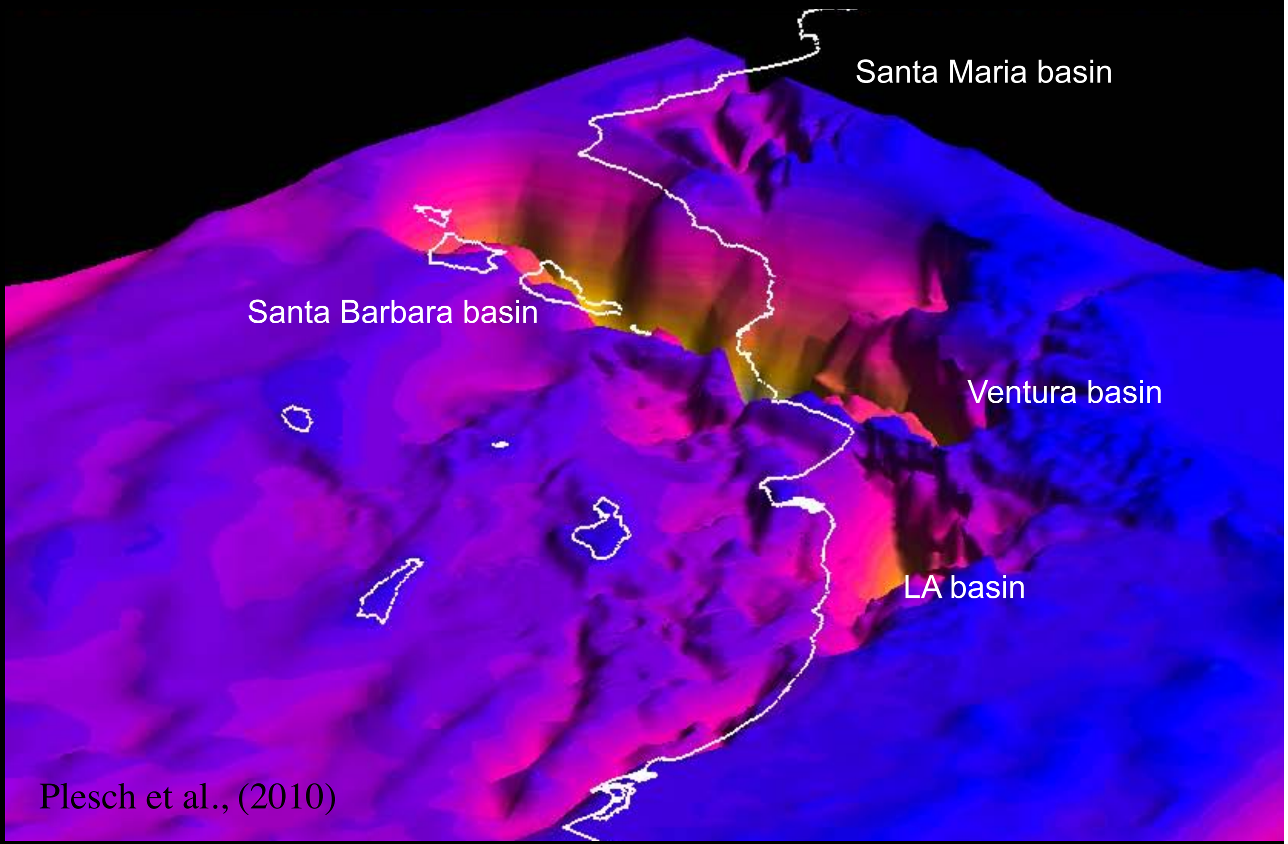


Tape et al., (2010)

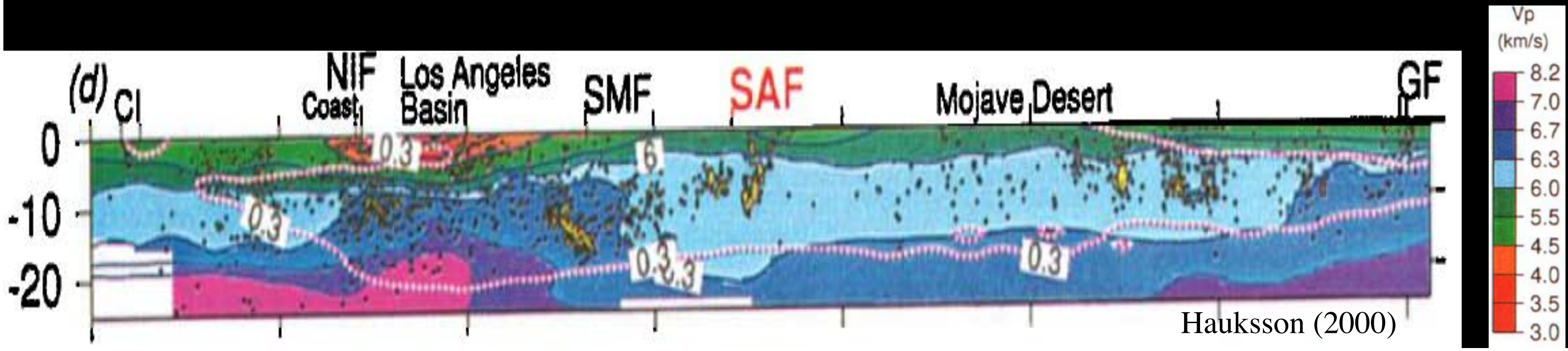
Basin structure of the California Crust

Coastal basins

- Southern California coastal basins (Los Angeles, Ventura-Santa Barbara, Santa Maria) formed during early Tertiary transtension associated with block rotations.
- Late Tertiary thrusting and sedimentation led to further basin subsidence.

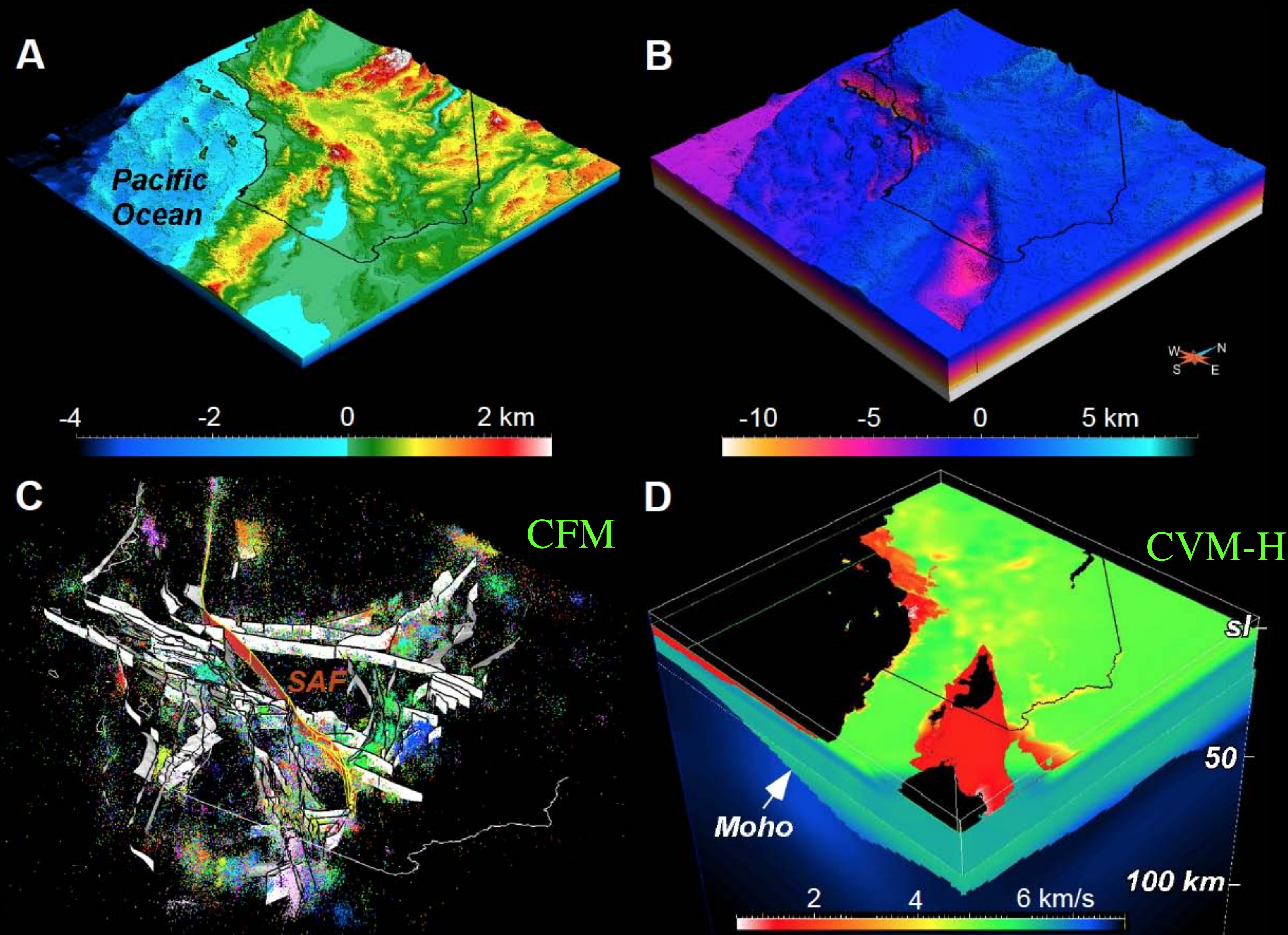


Plesch et al., (2010)



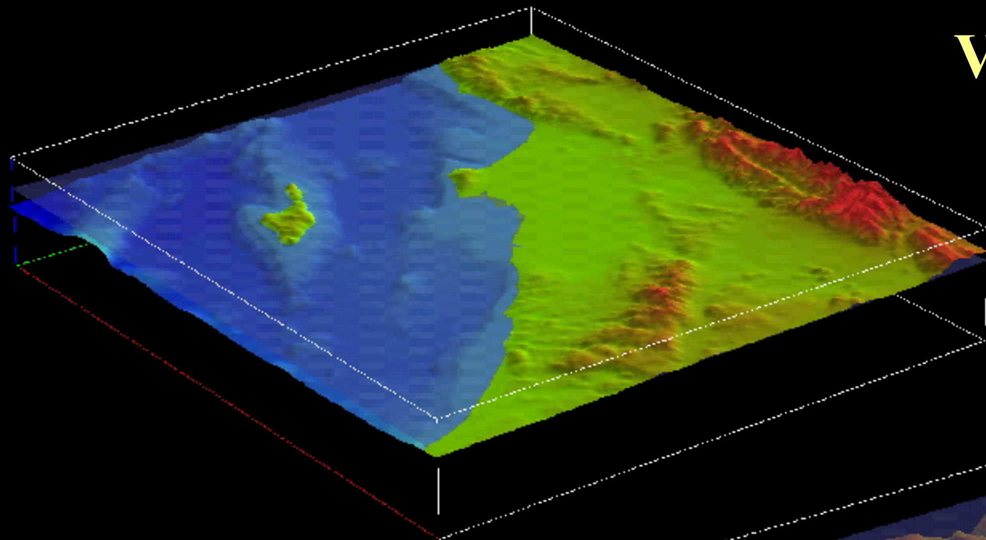
Hauksson (2000)

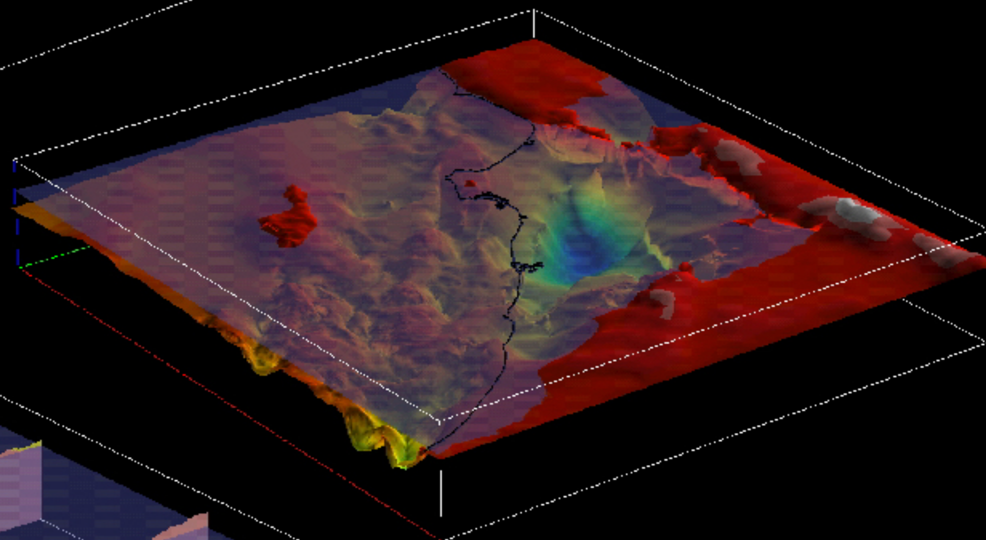
SCEC Unified Structural Representation (USR)

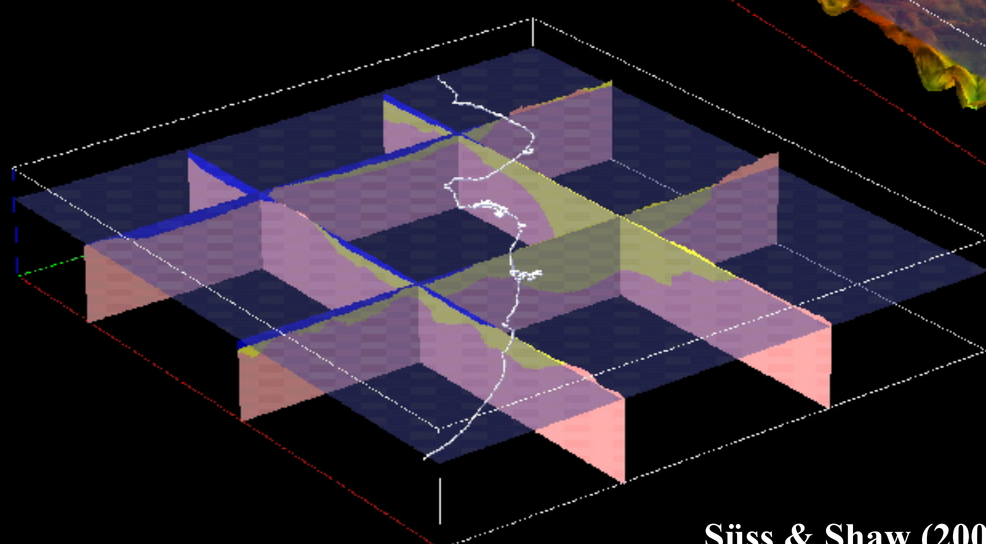


USR development workflow begins with the definition of geological and geophysical horizons that represent important velocity interfaces.

Volumetric description of basin sediments



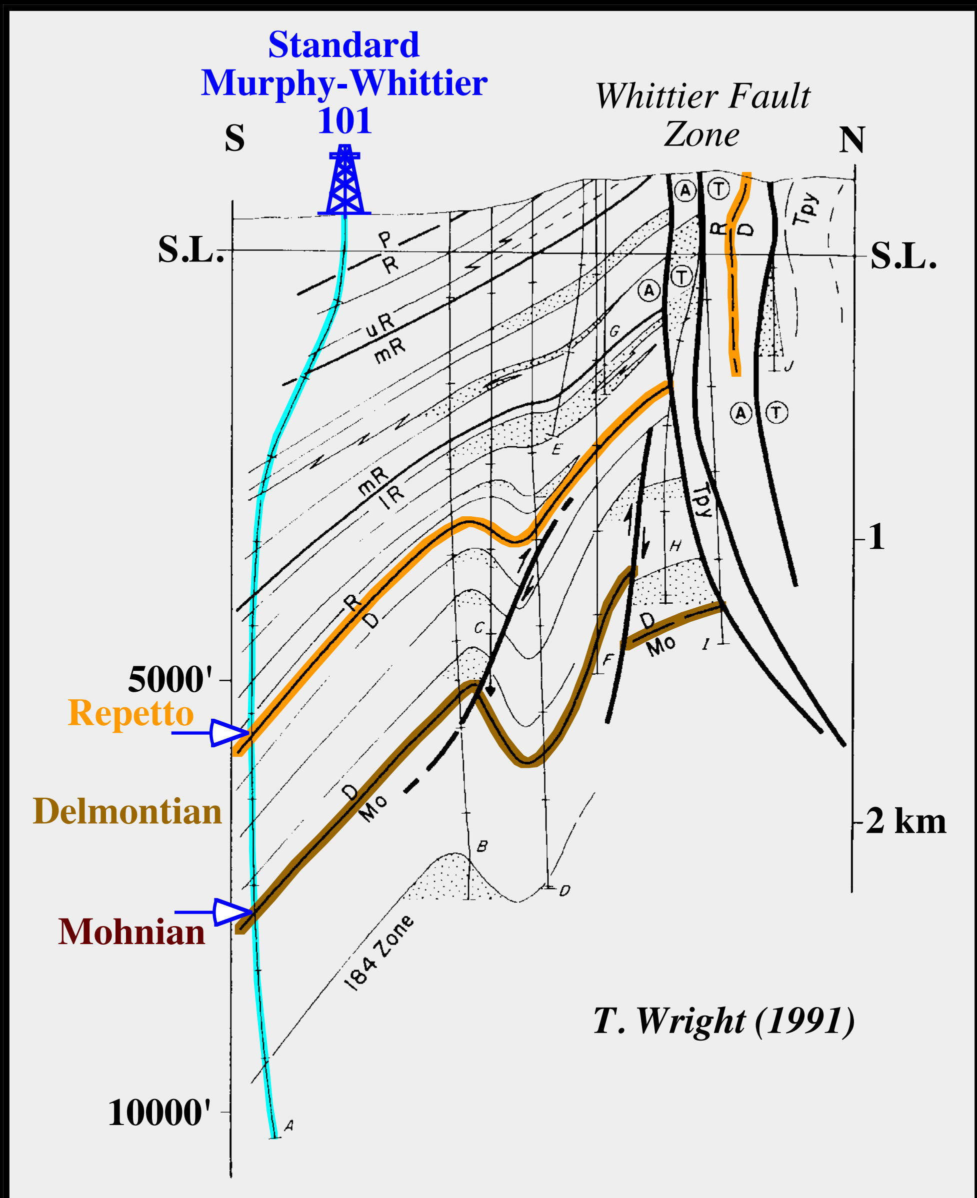




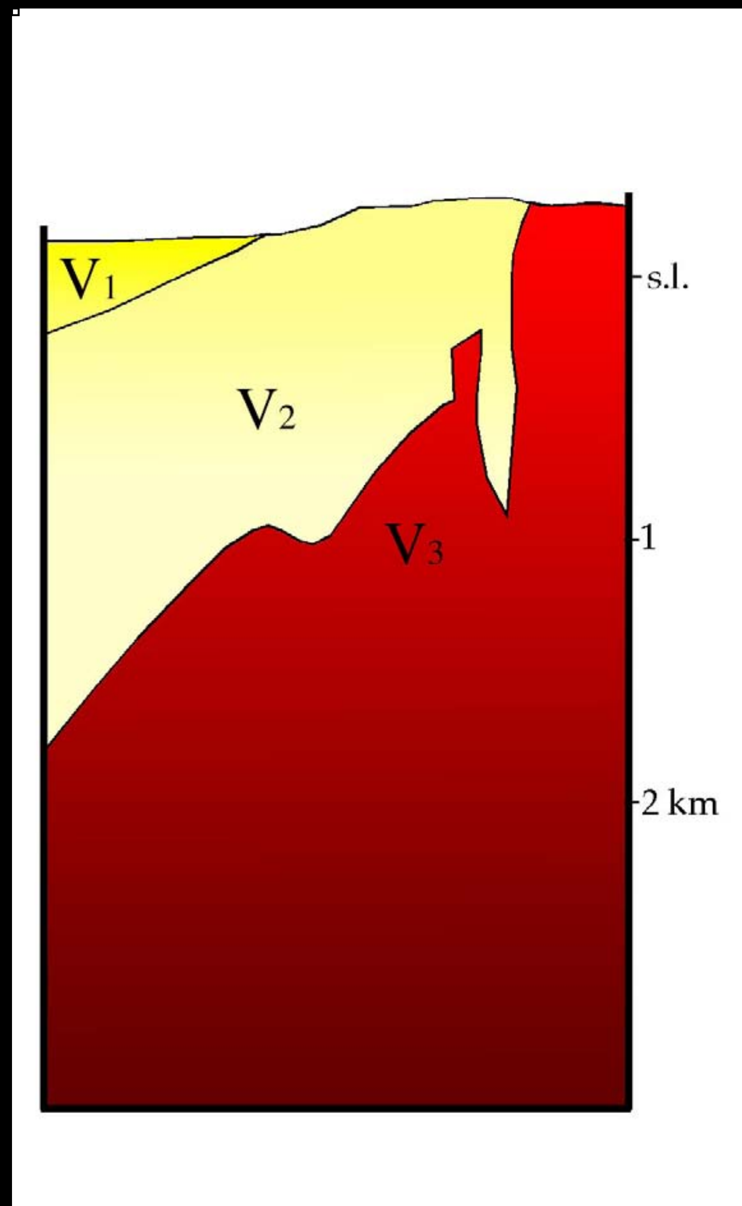
Süss & Shaw (2003)

Geological & geophysical surfaces in velocity modeling

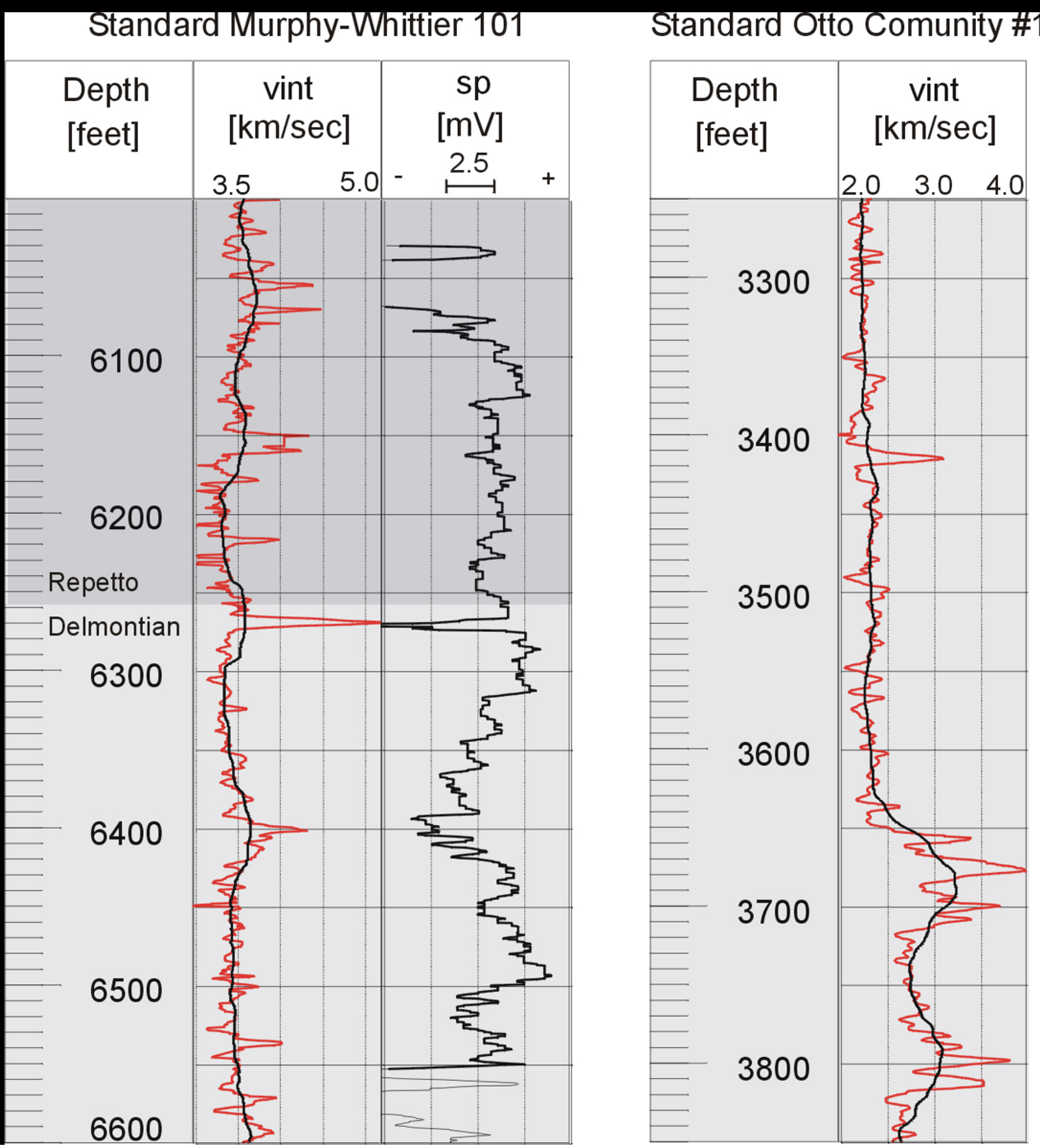
Geologic section

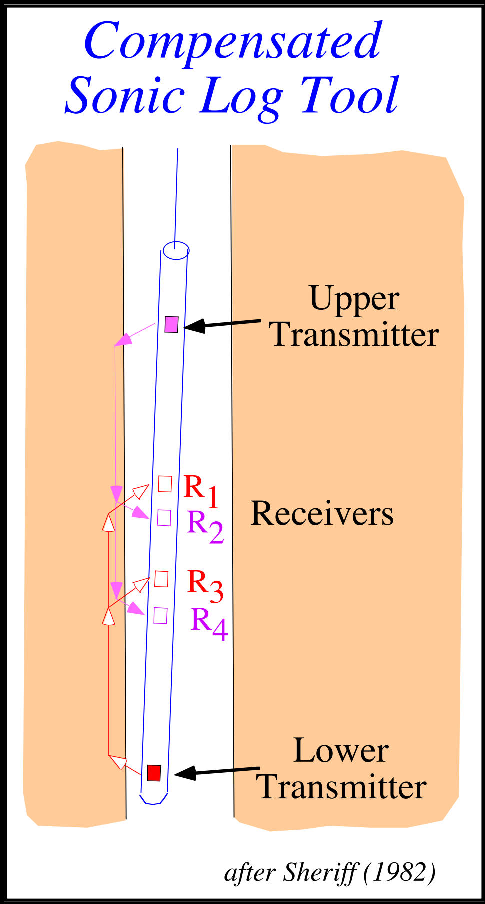


Velocity model



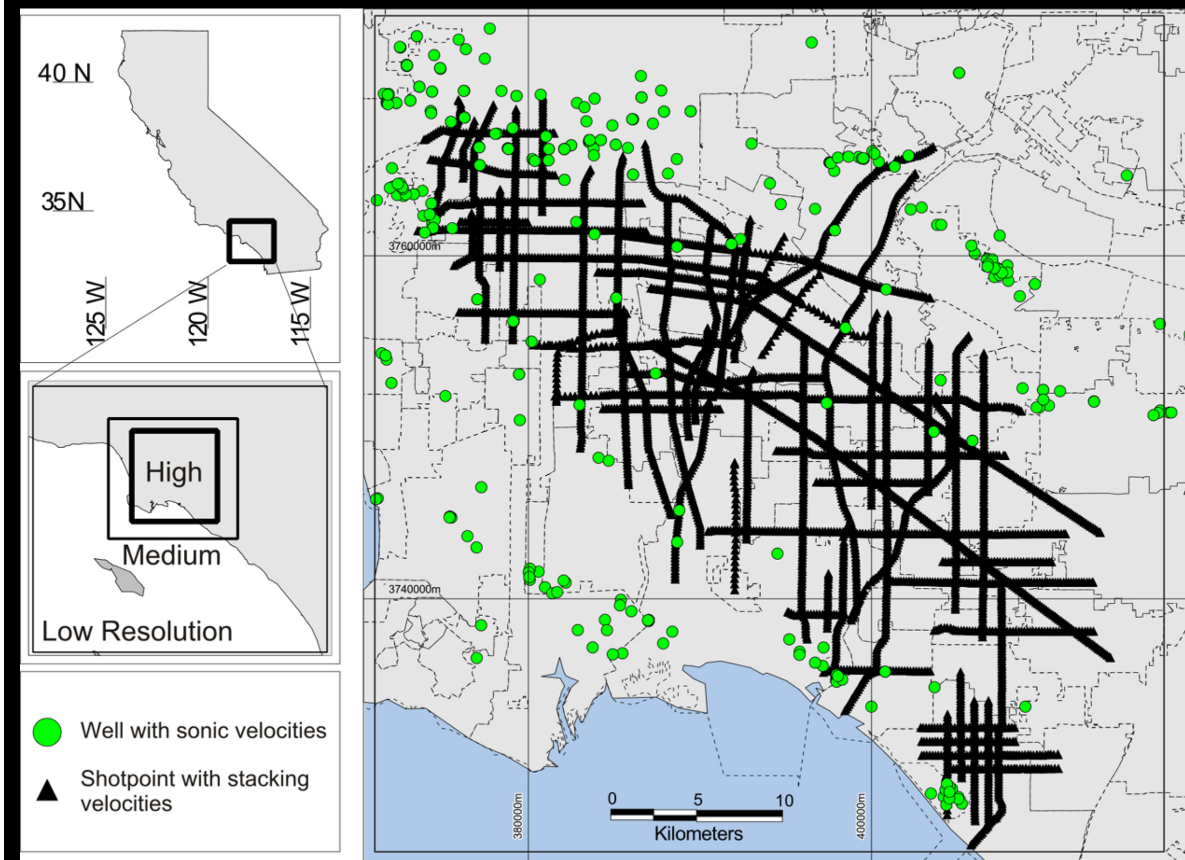
Industry sonic logs

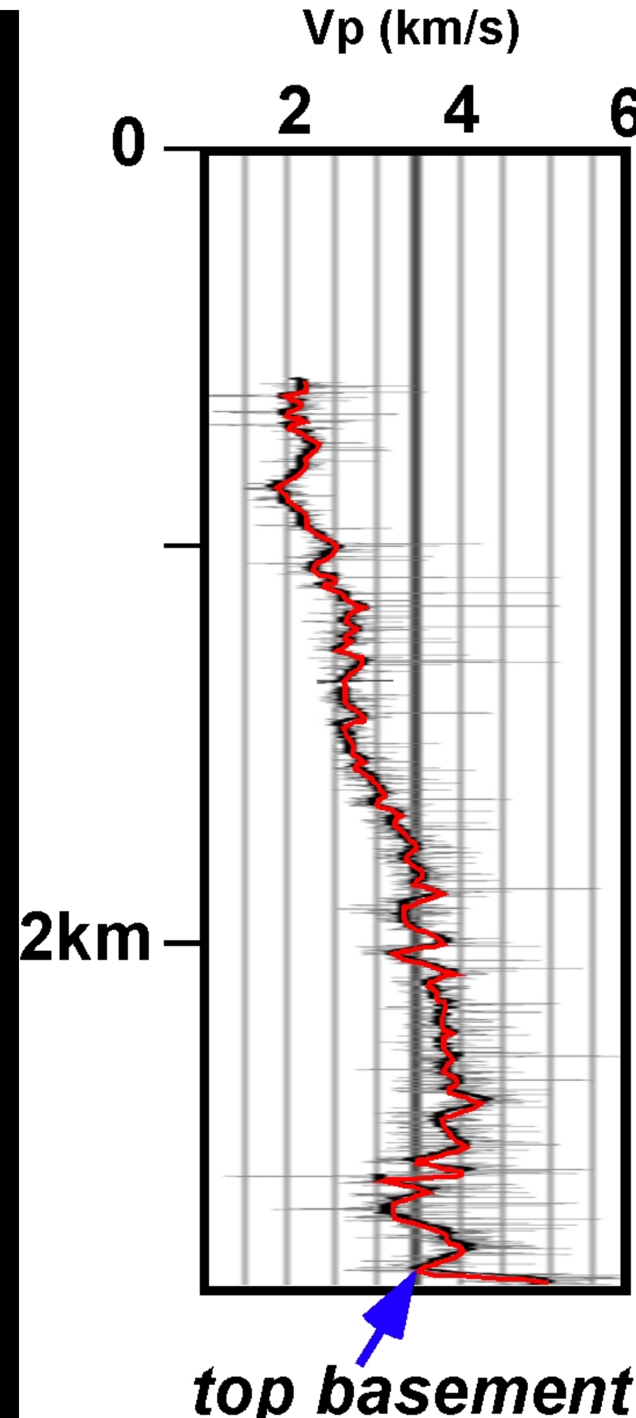




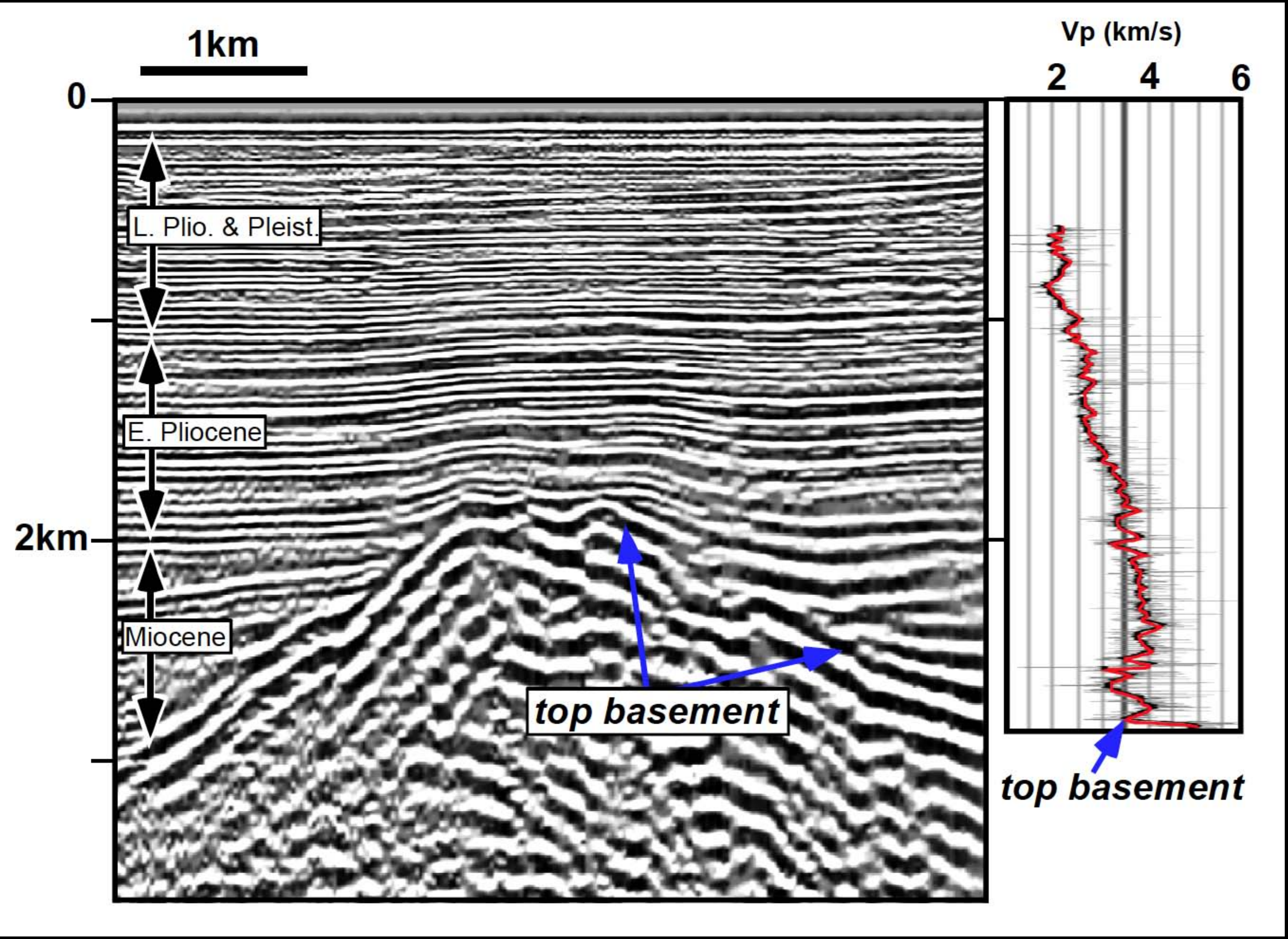
Süss & Shaw (2003)

Industry sonic logs

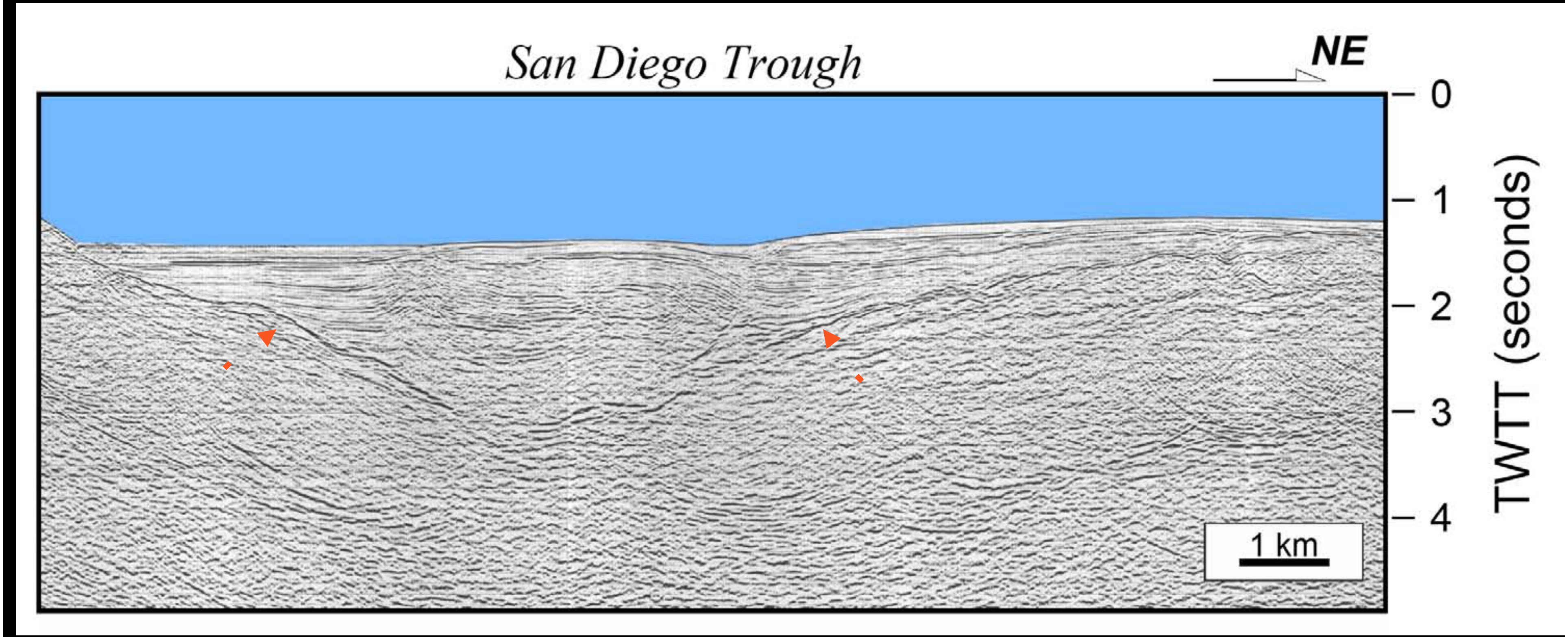




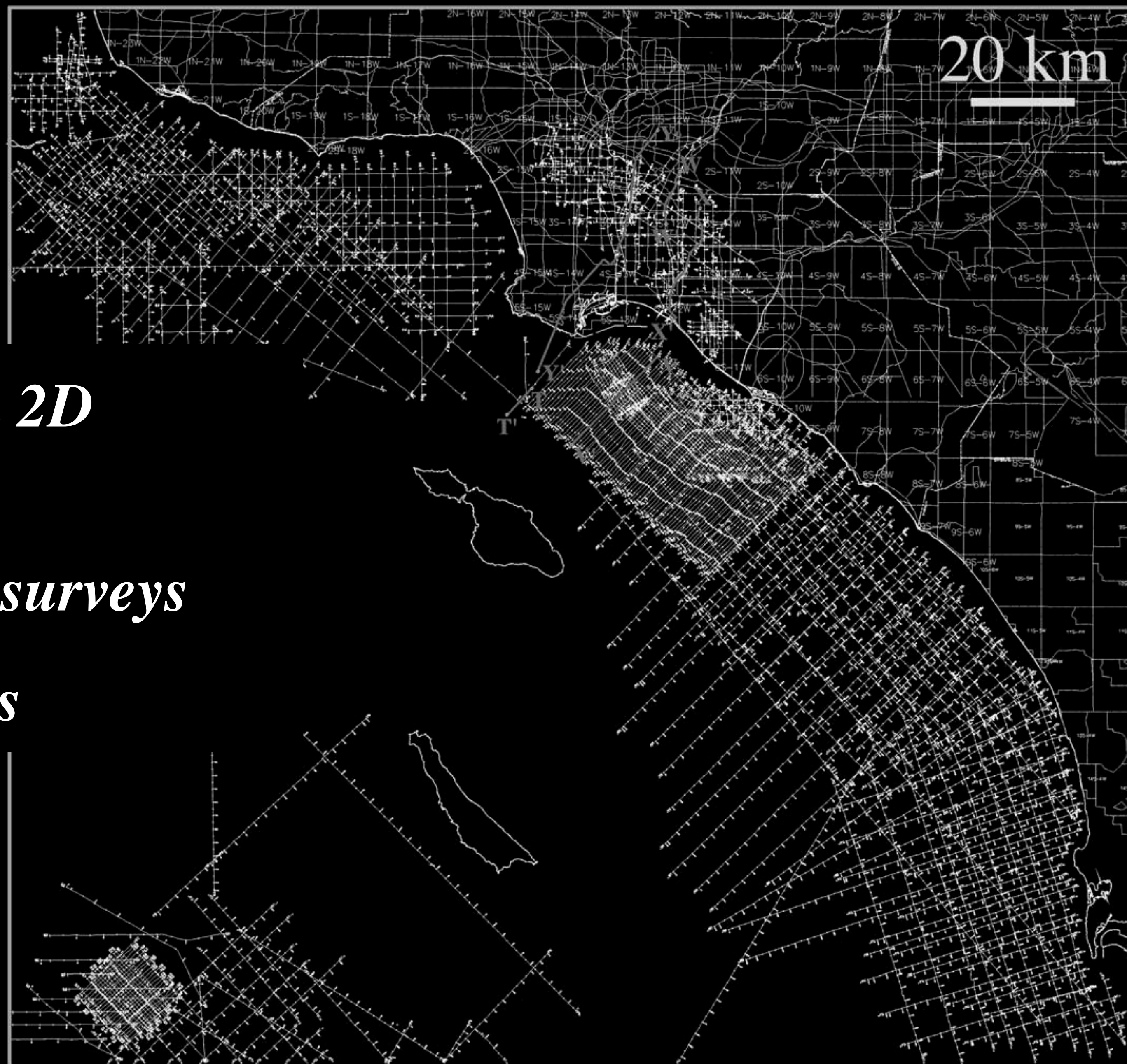
Defining the basement surface



Defining the basement surface



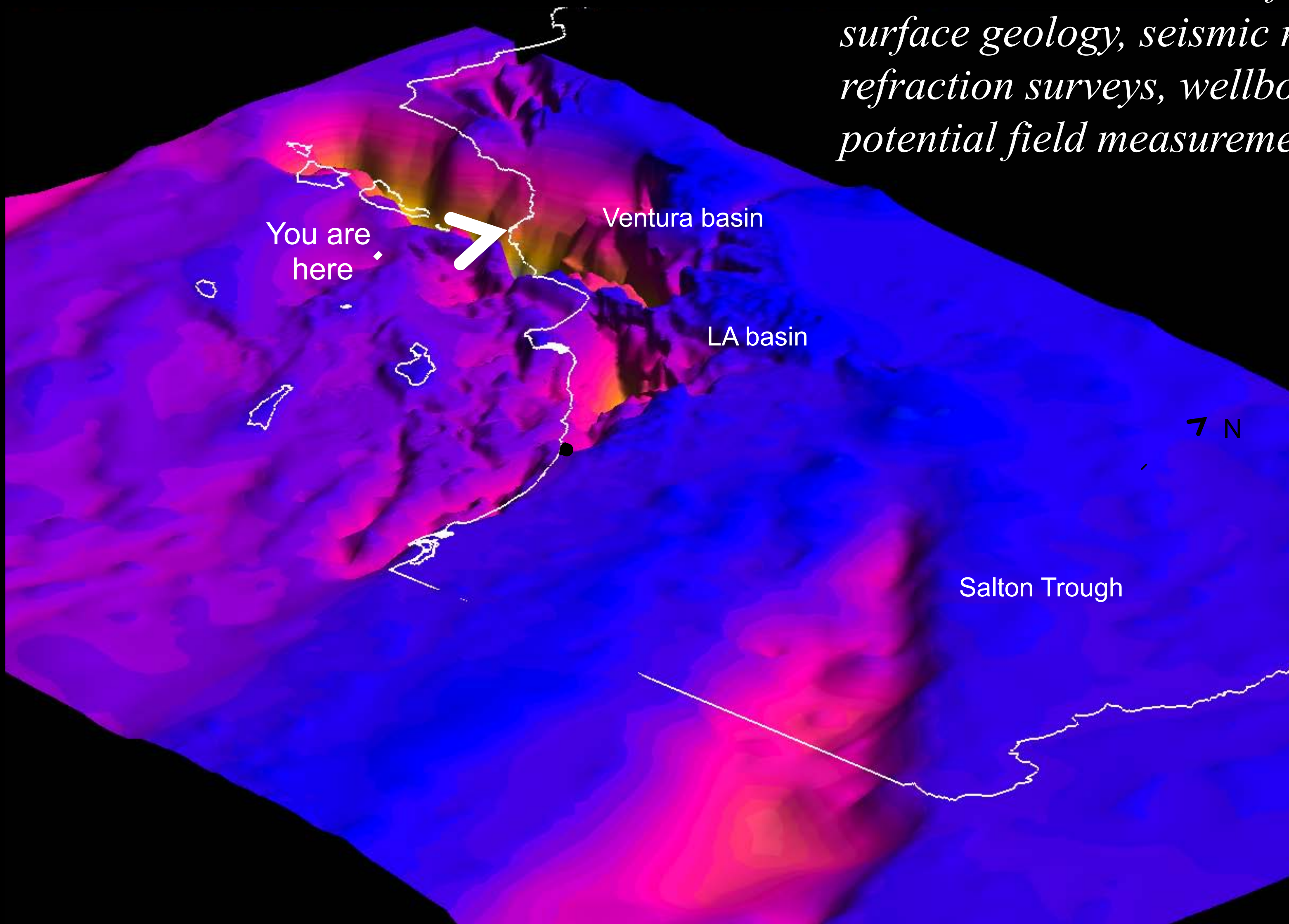
Industry data coverage



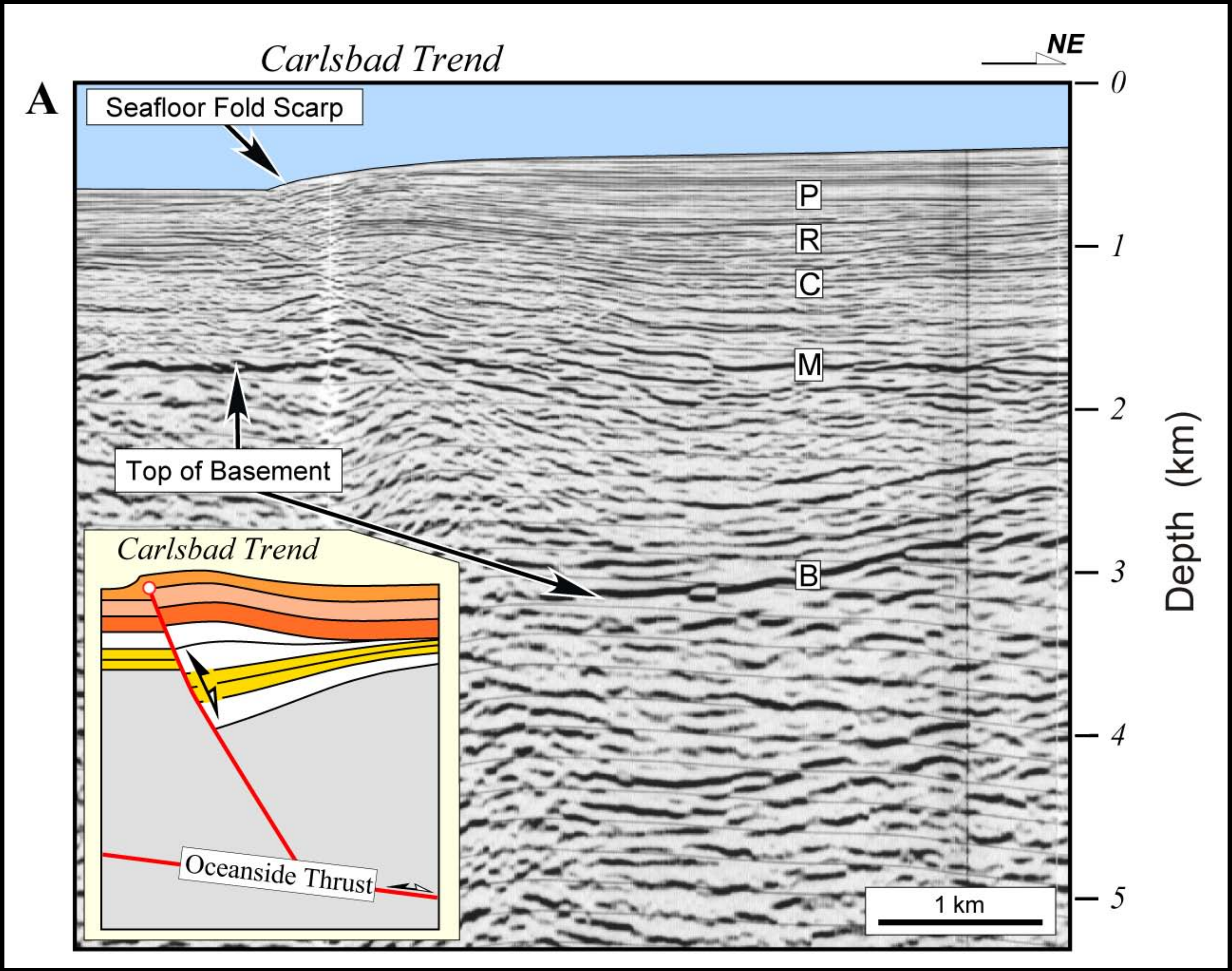
- *100,000 km 2D seismic data*
- *3D seismic surveys*
- *10,000 wells*

Basement structure in the SCEC CVM/USR

Basement structure is defined by surface geology, seismic reflection and refraction surveys, wellbore data, and potential field measurements.

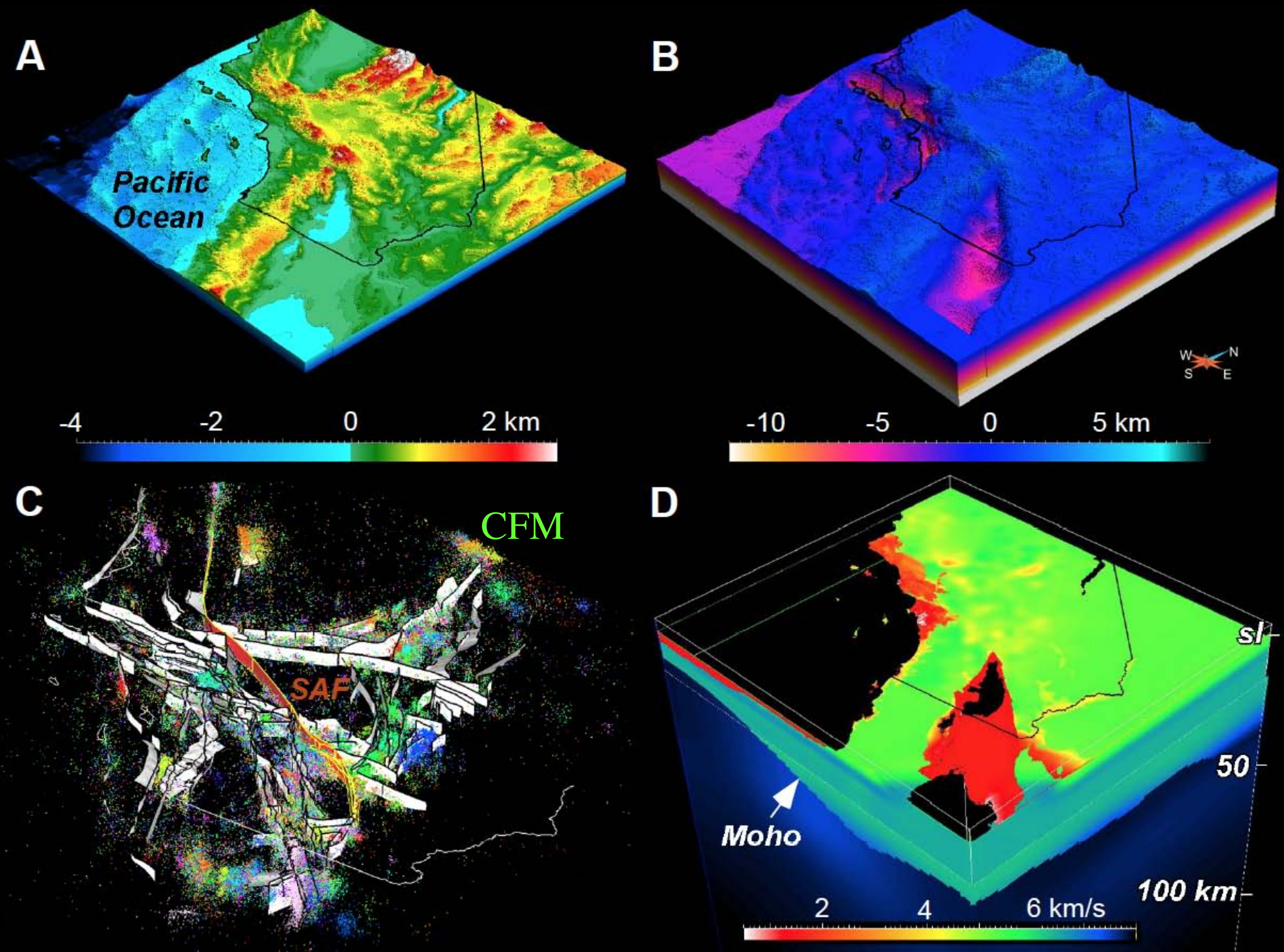


Basement structure and faults



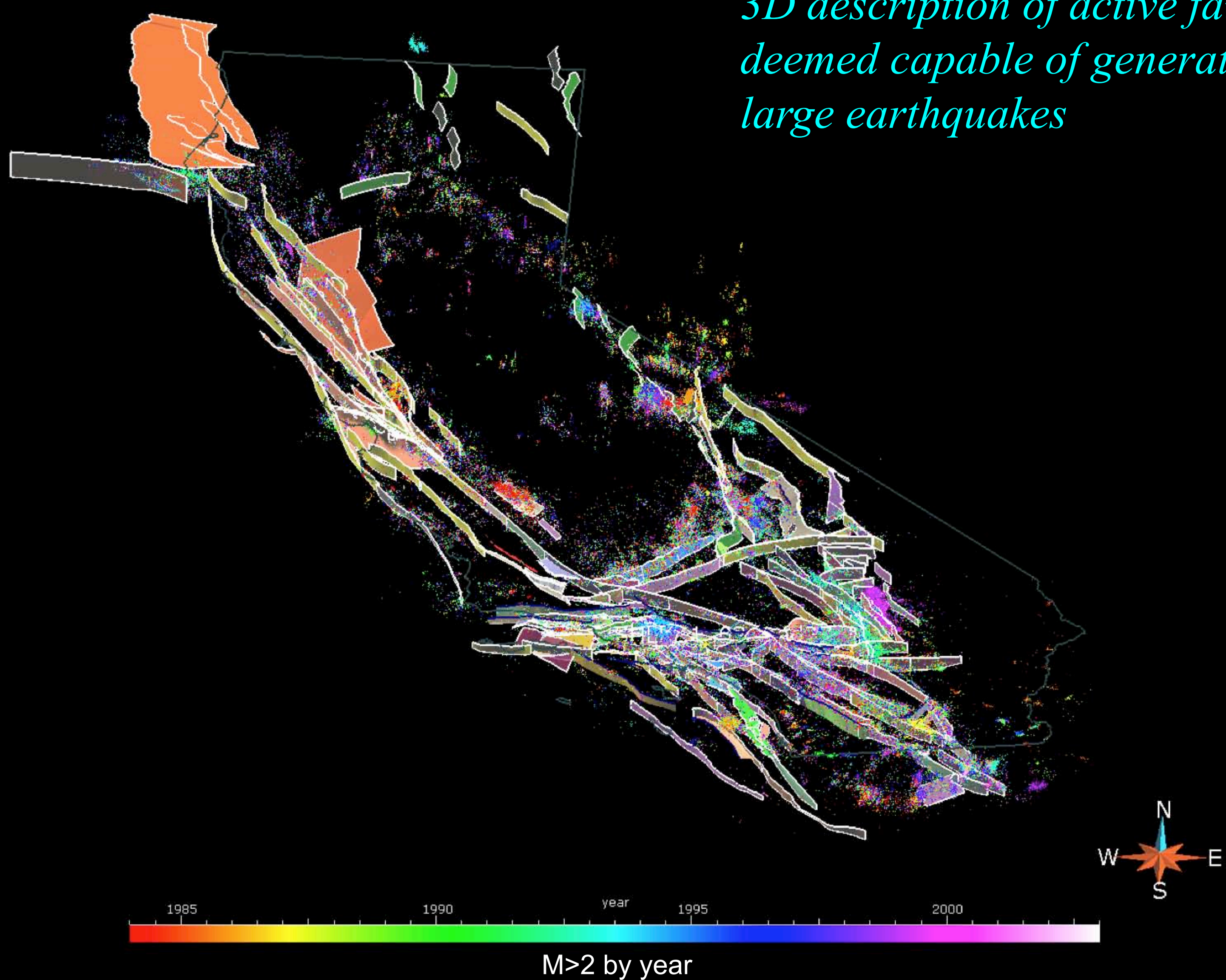
Faults locally offset the basement and other geological horizons, and thus influence velocity structure.

SCEC Unified Structural Representation (USR)

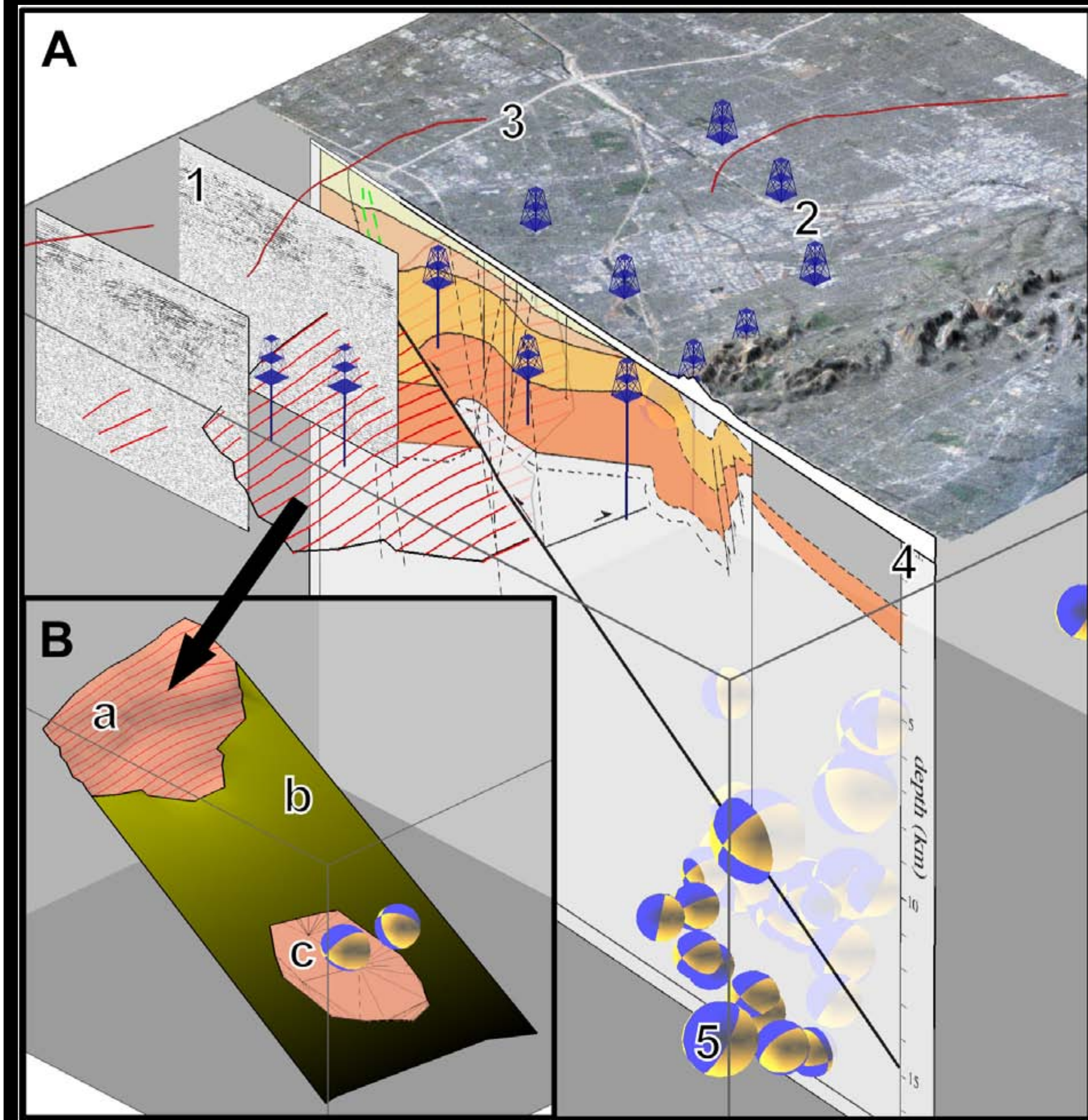


SCEC Community Fault Model (CFM)

3D description of active faults that are deemed capable of generating moderate to large earthquakes



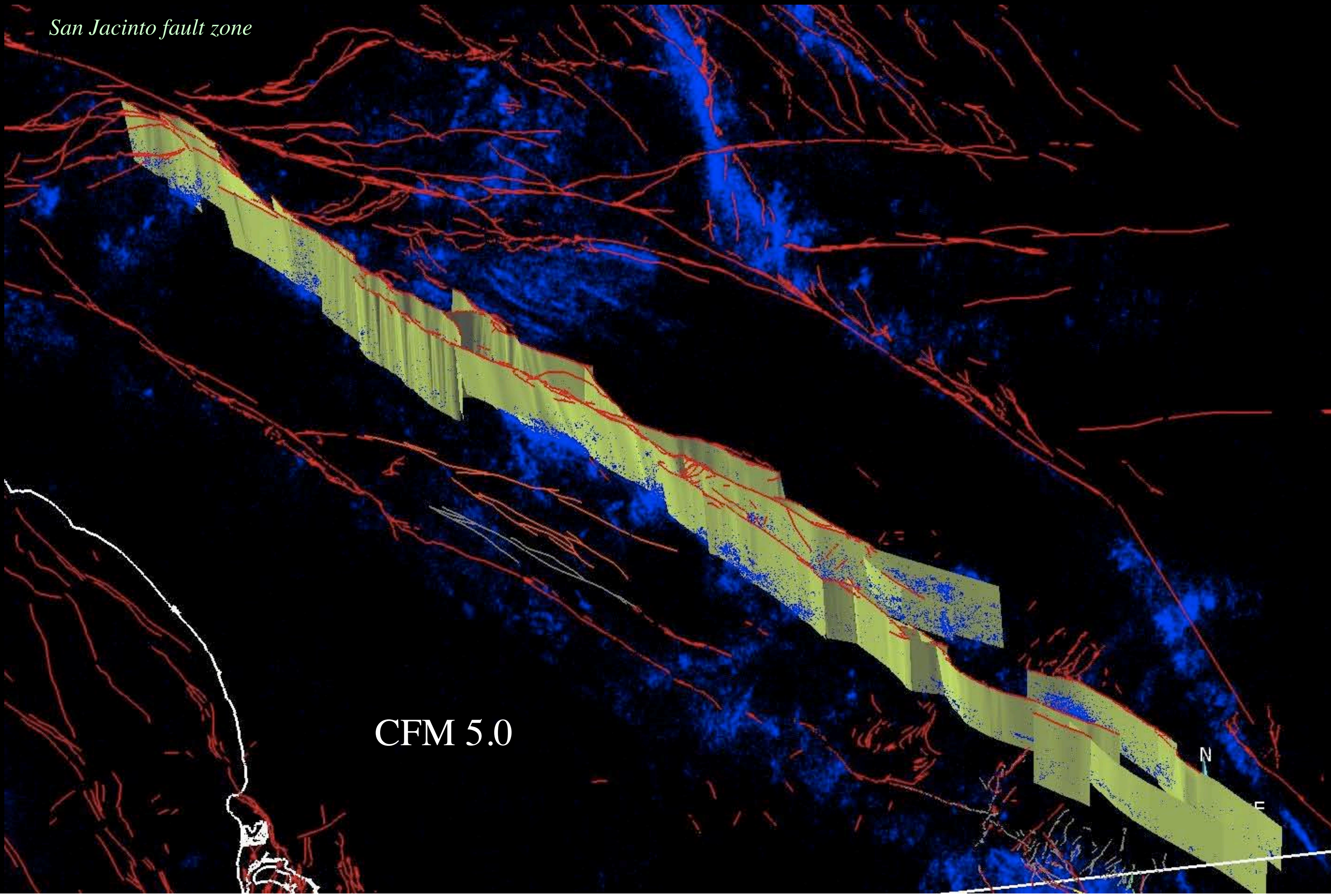
Community Fault Model (CFM)



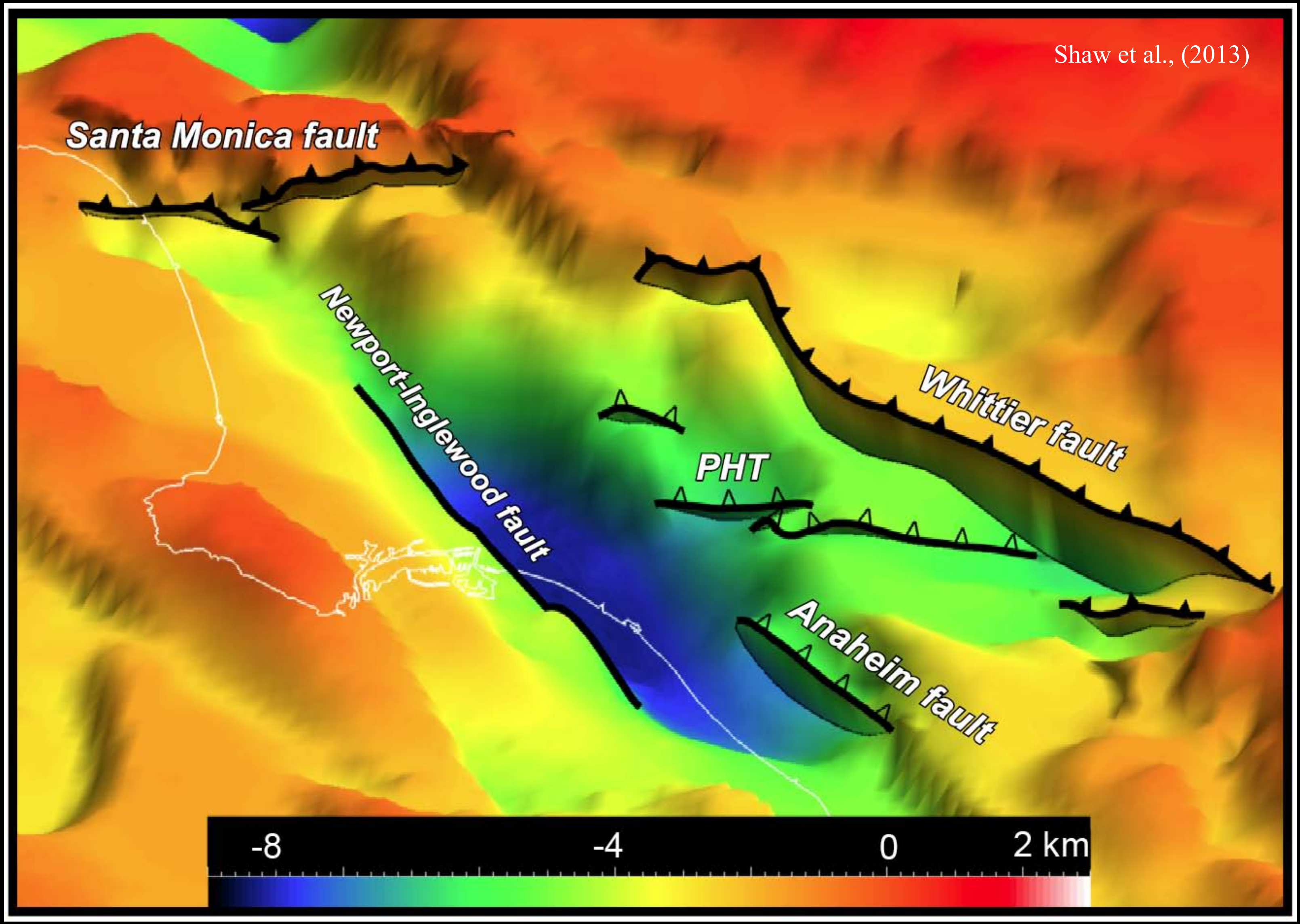
- integrates many types of data that constrain fault geometries
- interpolated and extrapolated fault patches
- alternative fault representations

Plesch et al., (2005)

***CFM 5.0** – many faults are more highly segmented, and include more precise segment linkages based on Qfault traces and seismicity.*

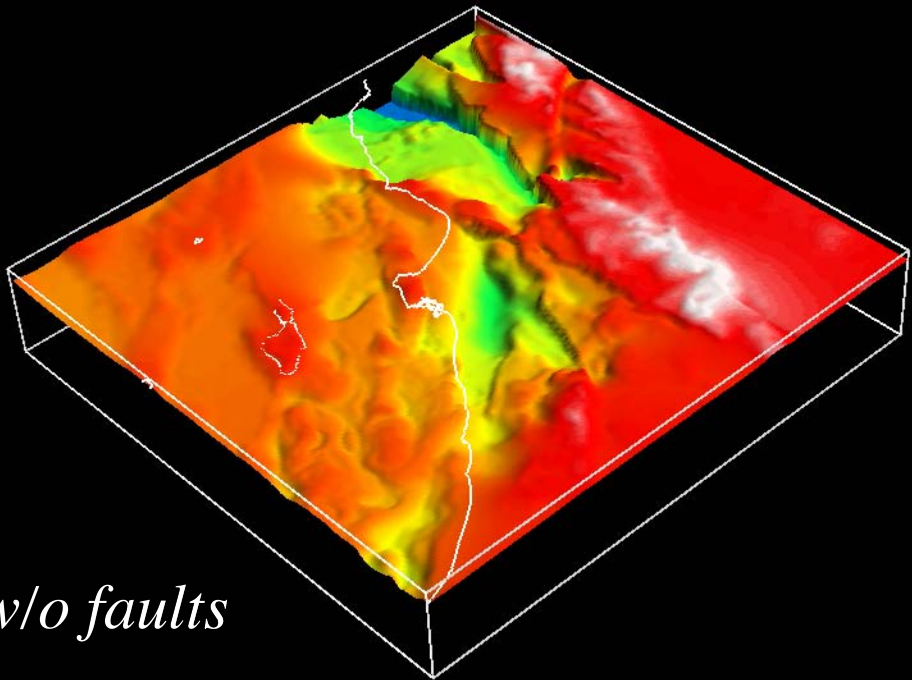


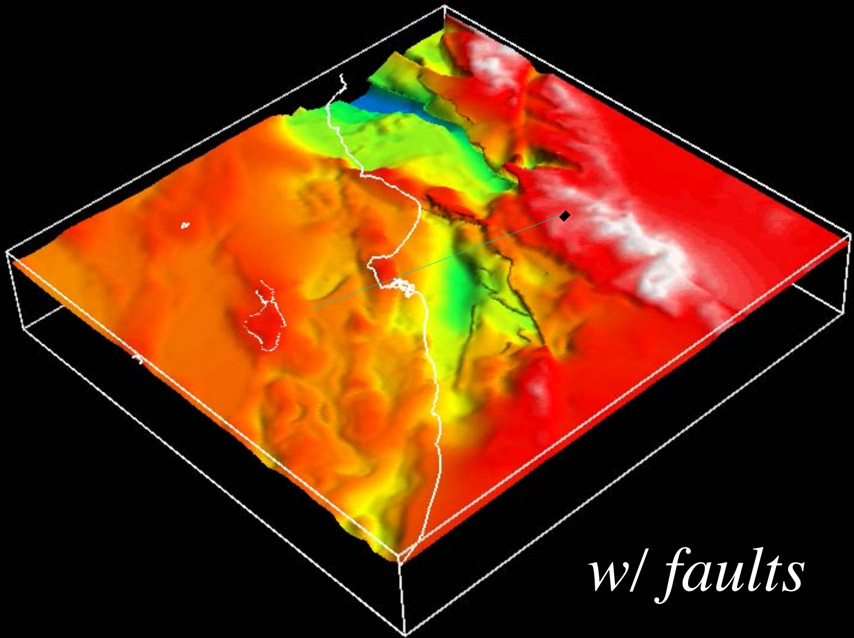
Faulted basement surface



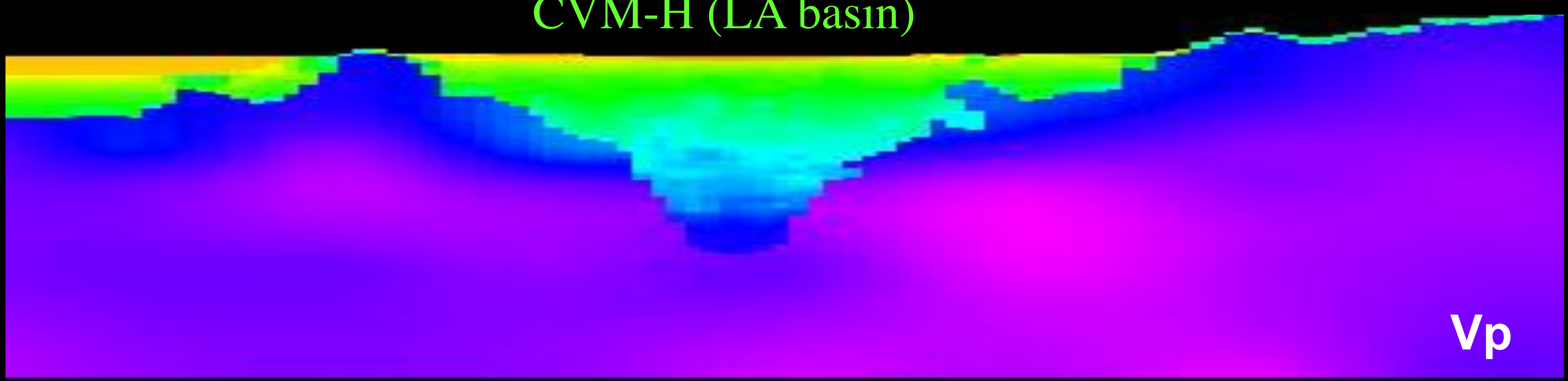
The locations and displacements of major faults are represented in the geologic surfaces that comprise the USR.

Basement structure in the SCEC CVM-H

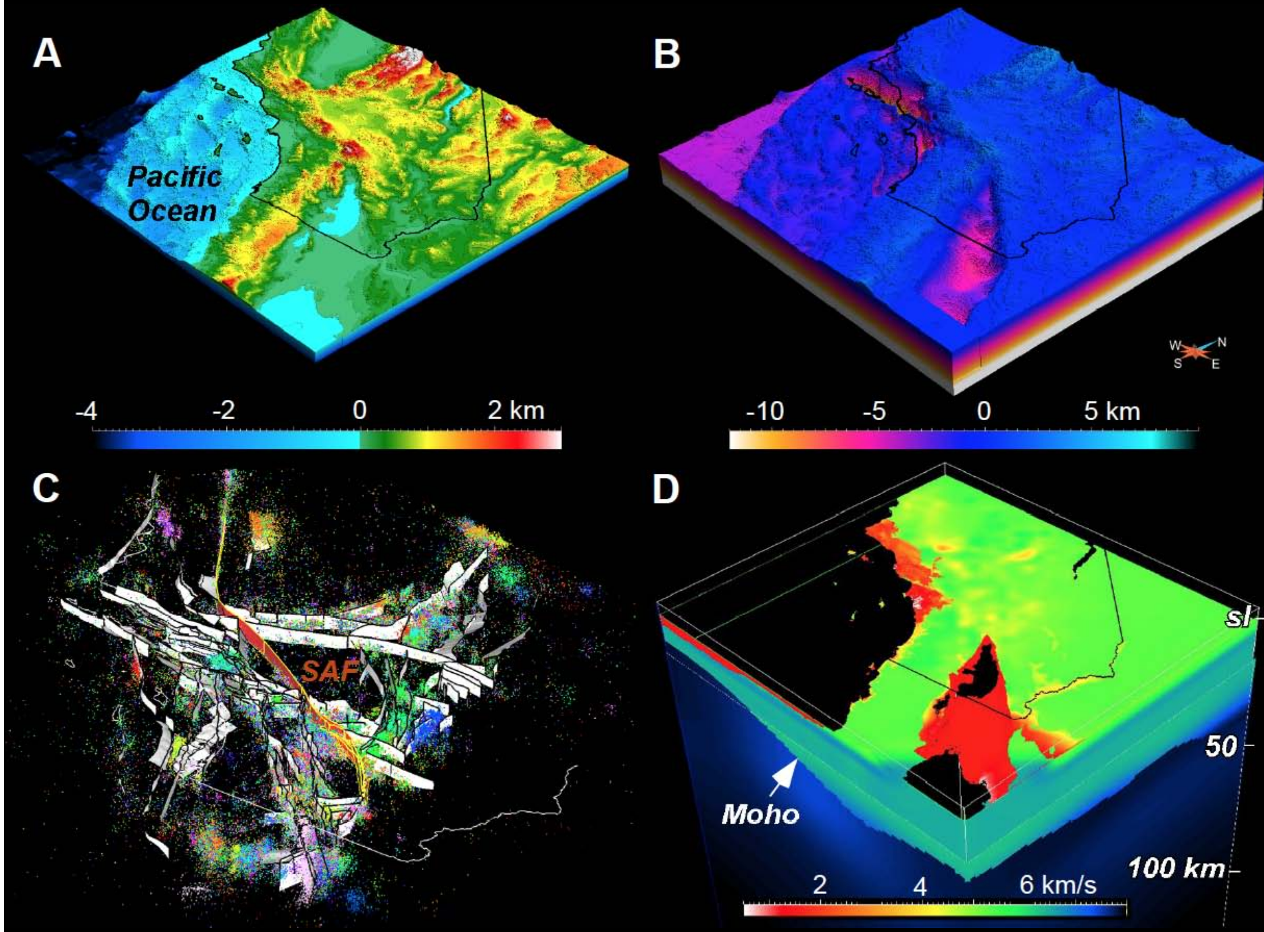




CVM-H (LA basin)



SCEC Unified Structural Representation (USR) Workflow



1) Definition of geological and geophysical horizons

2) Incorpration of fault locations and displacements

3) Parameterization of sediment velocities

SCEC CVMS 4.0 – Sediment Velocities

(Magistrale, Day, Clayton, & Graves, 2000, 2005)

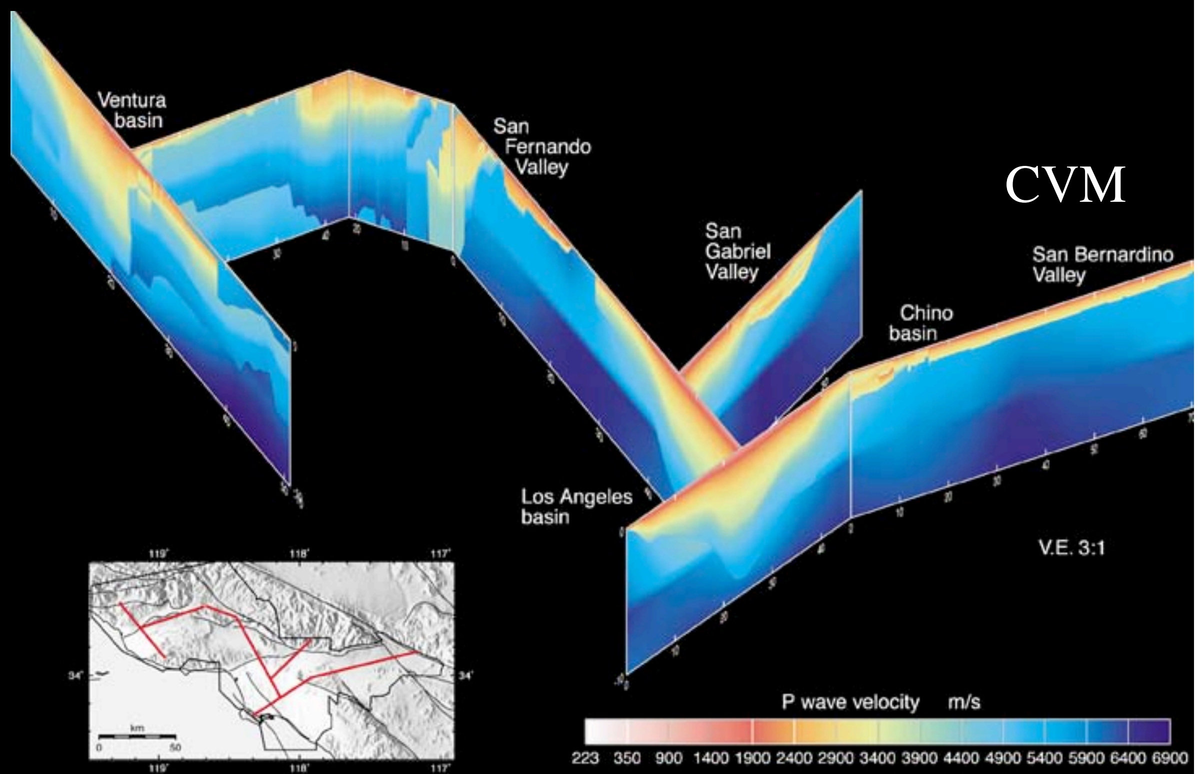
- Vp is defined at stratigraphic boundaries as a function of depth(Z) and age (T) using Faust's law:

$$v_{\text{int}} = \alpha(ZT)^{1/6}$$

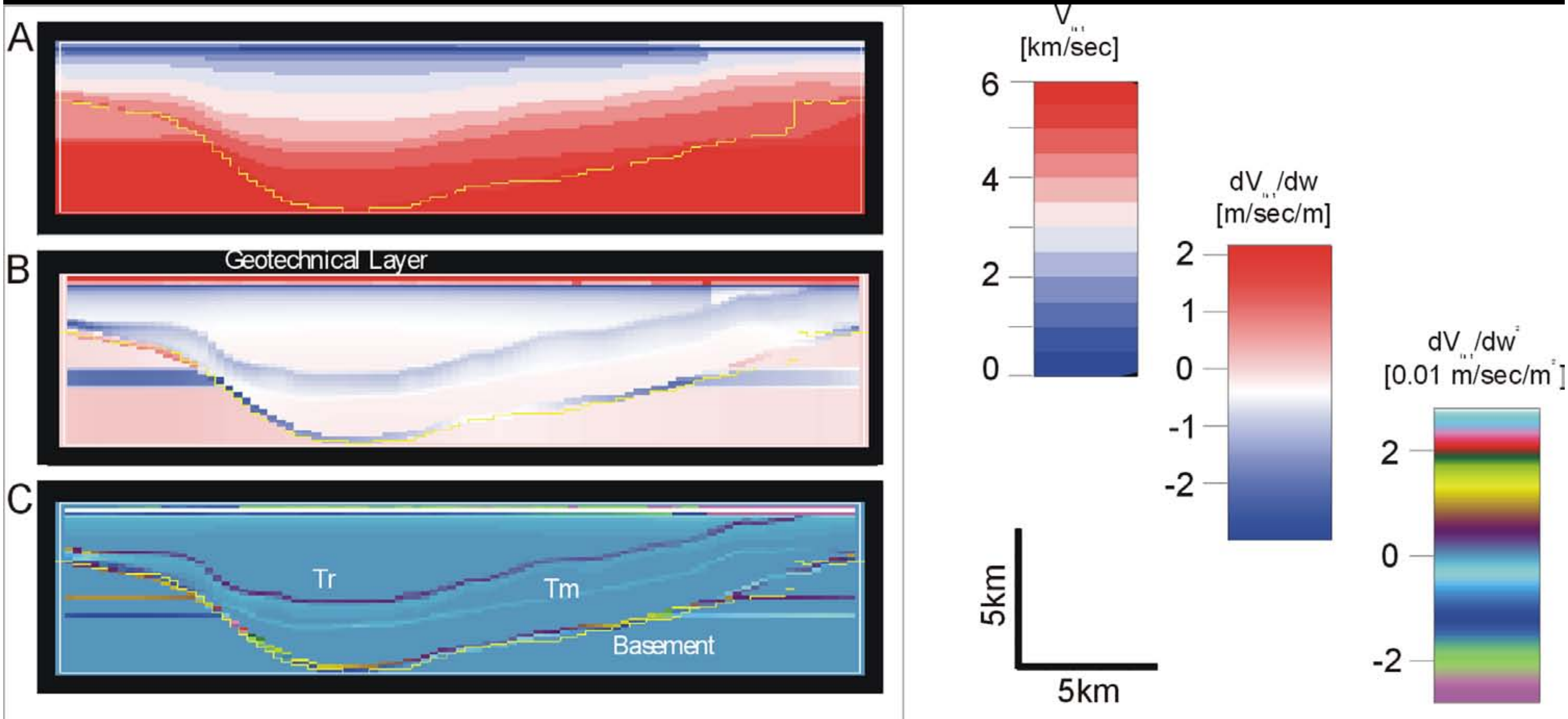
- relation is calibrated using well control

- Vp is linearly interpolated between stratigraphic horizons

CVM



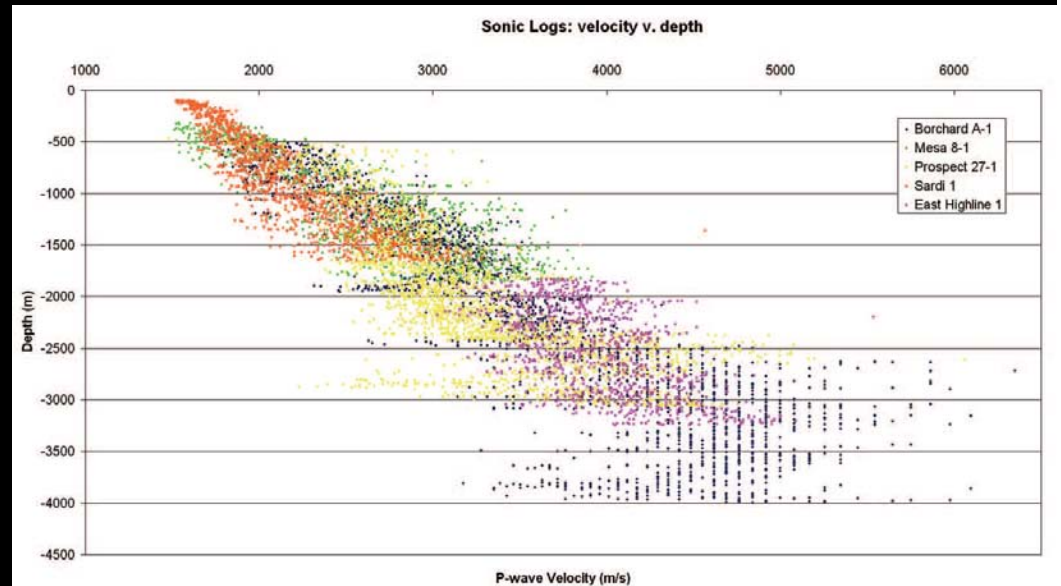
CVM-S – Rule based



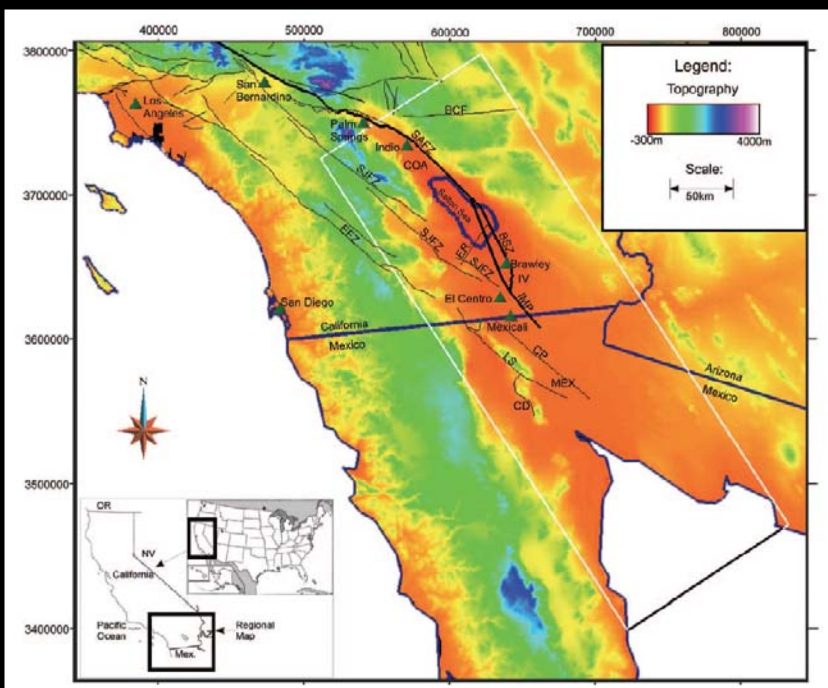
Magistrale et al., (2000)

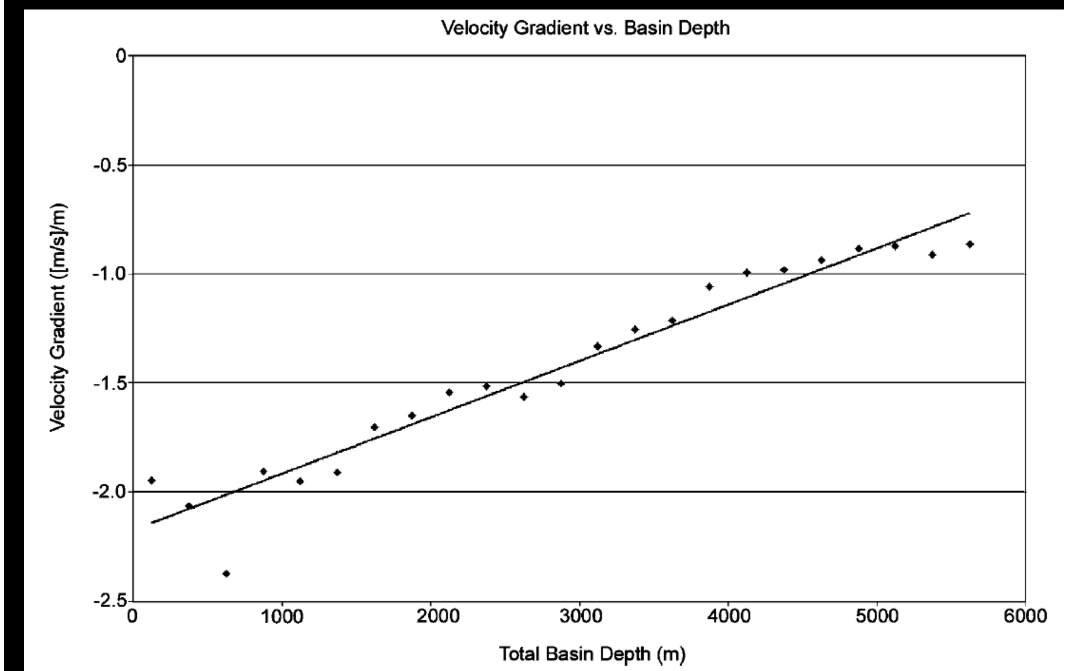
Additional parameters to constrain velocity structure

Velocity gradients as a function of total basin depth



Salton Trough

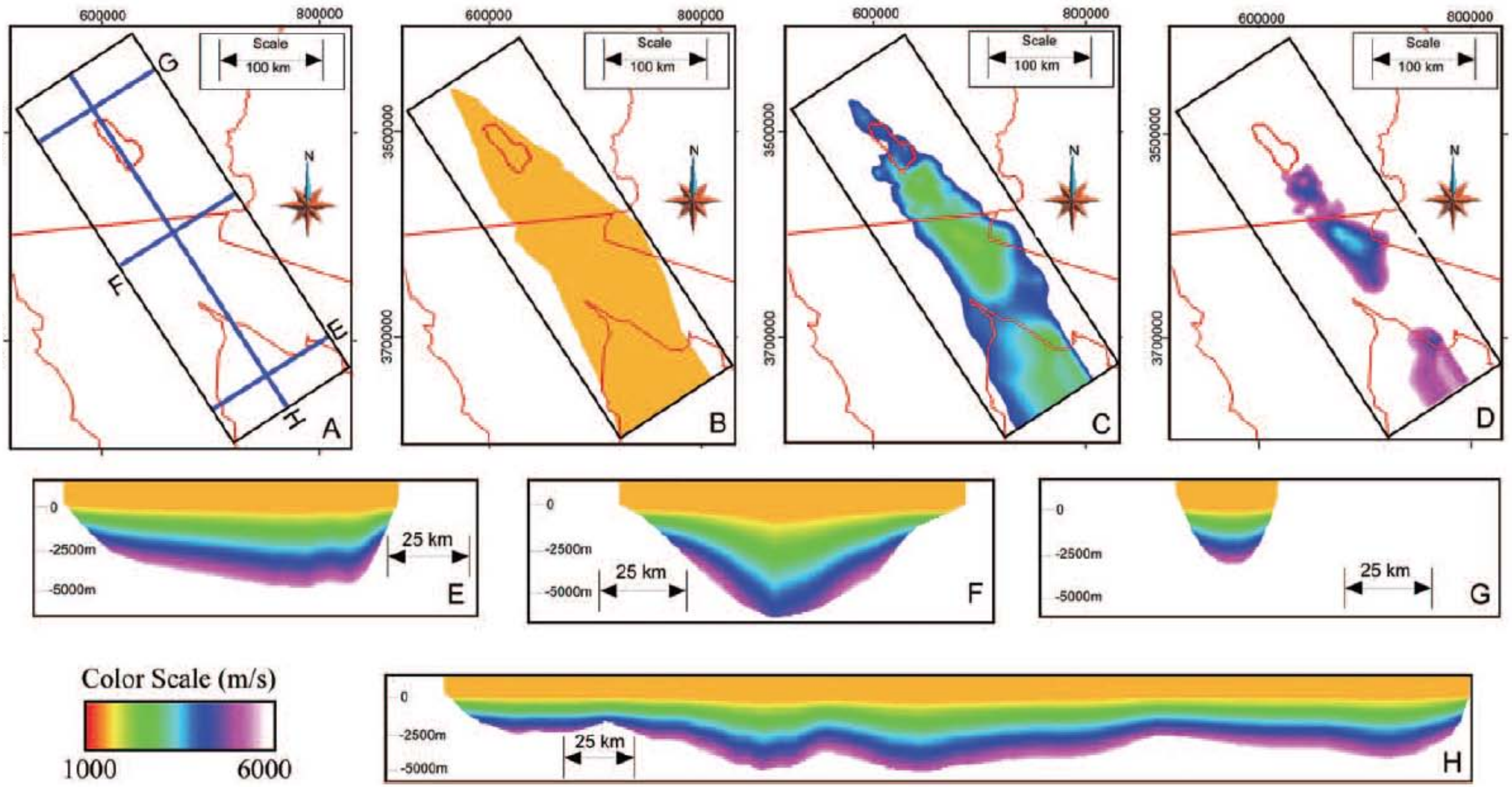




Lovely et al., (2007)

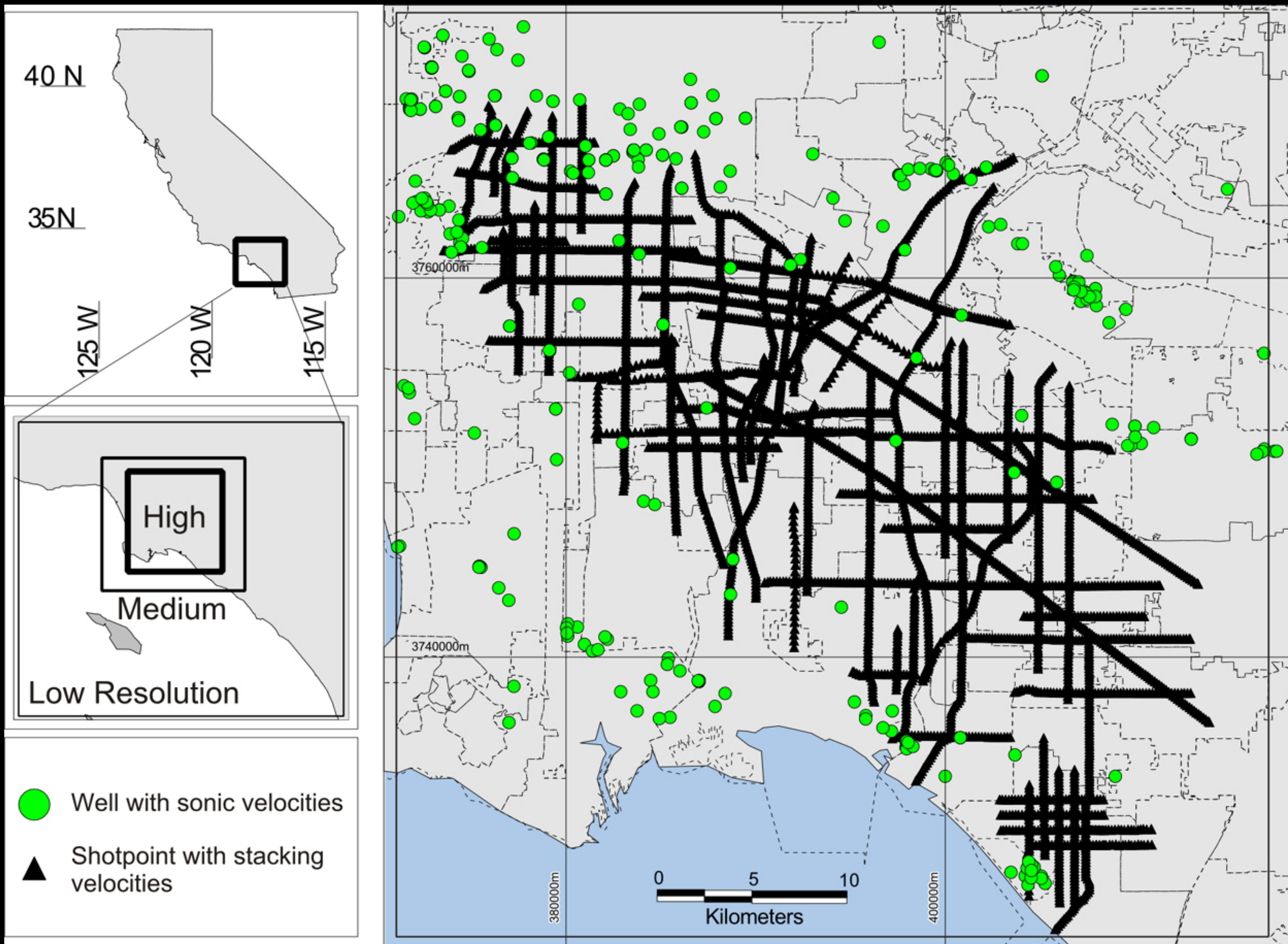
Velocity as a function of depth and total basin depth

Salton Trough

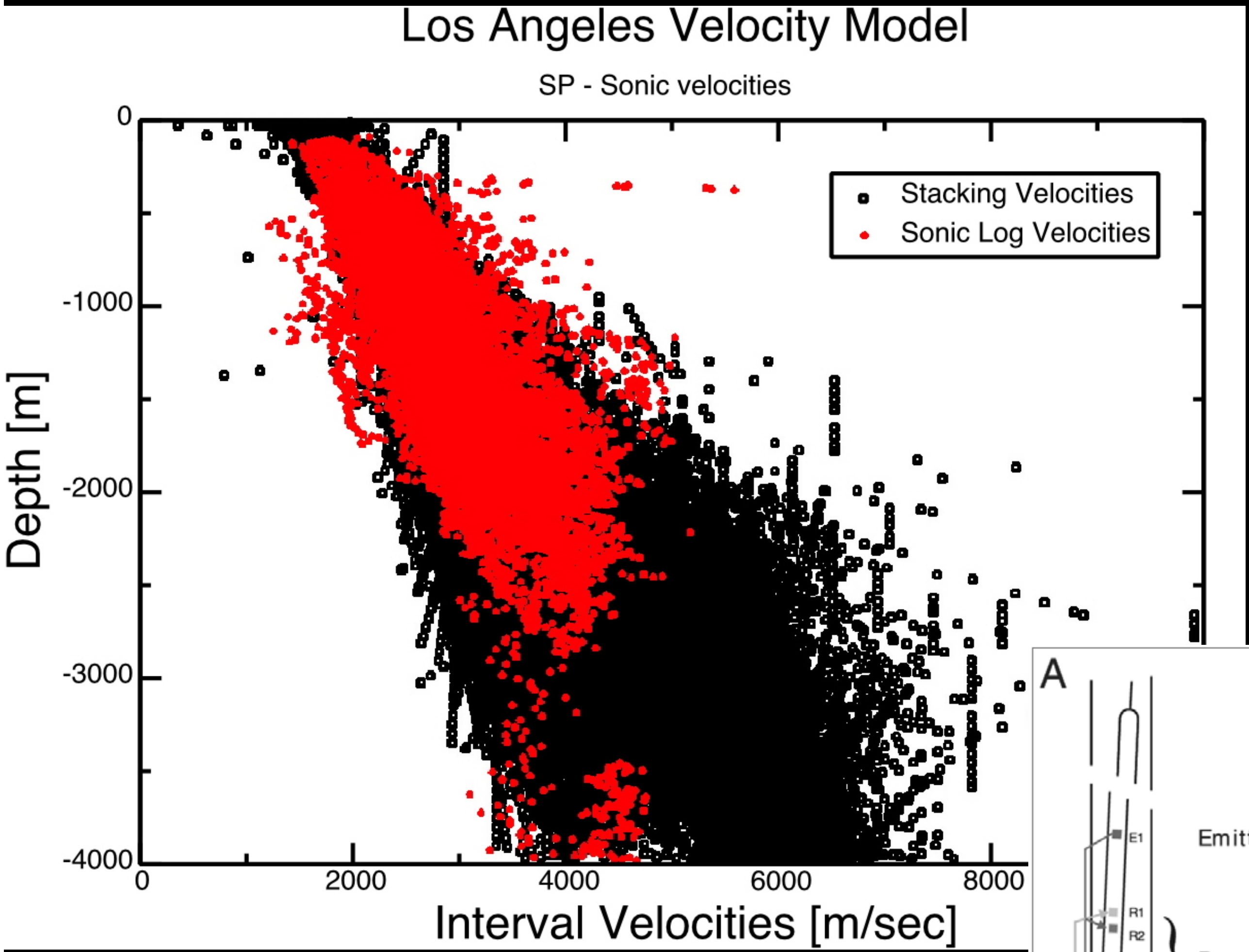


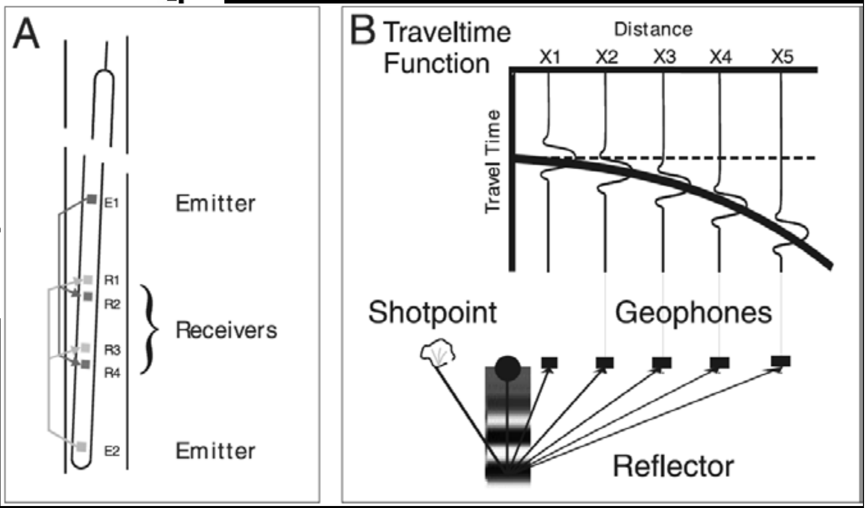
Lovely et al., (2007)

Velocity parameterization through geostatistical interpretation



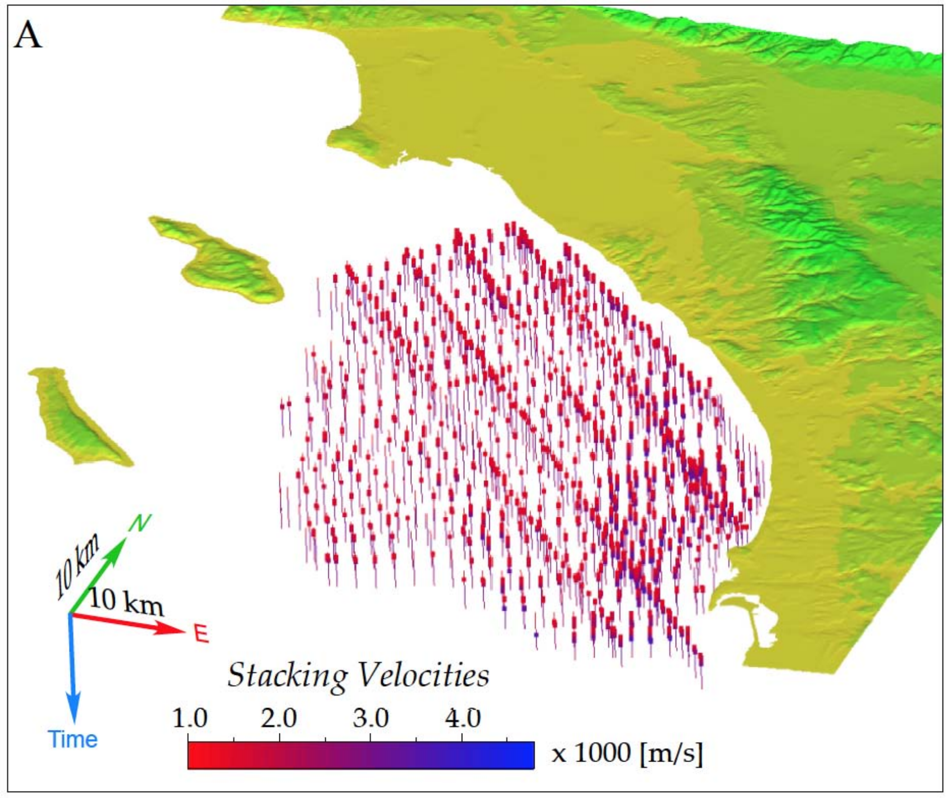
Industry velocity data





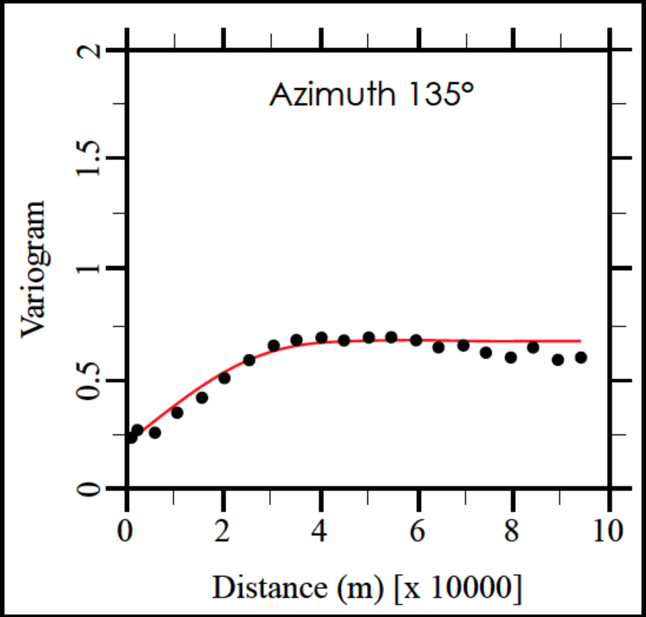
Velocity parameterization through kriging

Velocity data in Inner California Borderlands

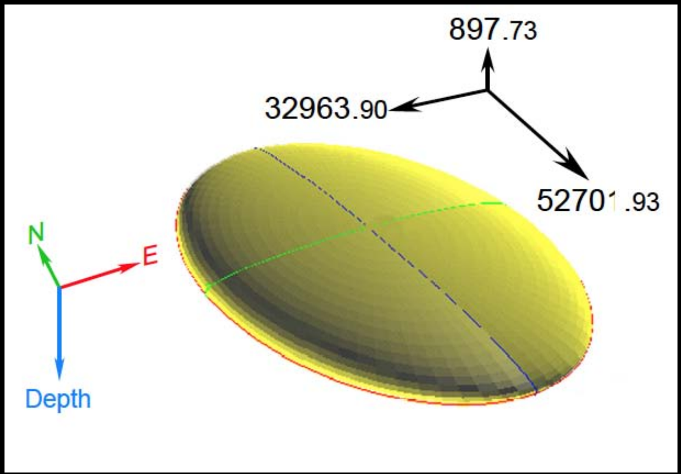


Rivero et al., 2004

Variance analysis

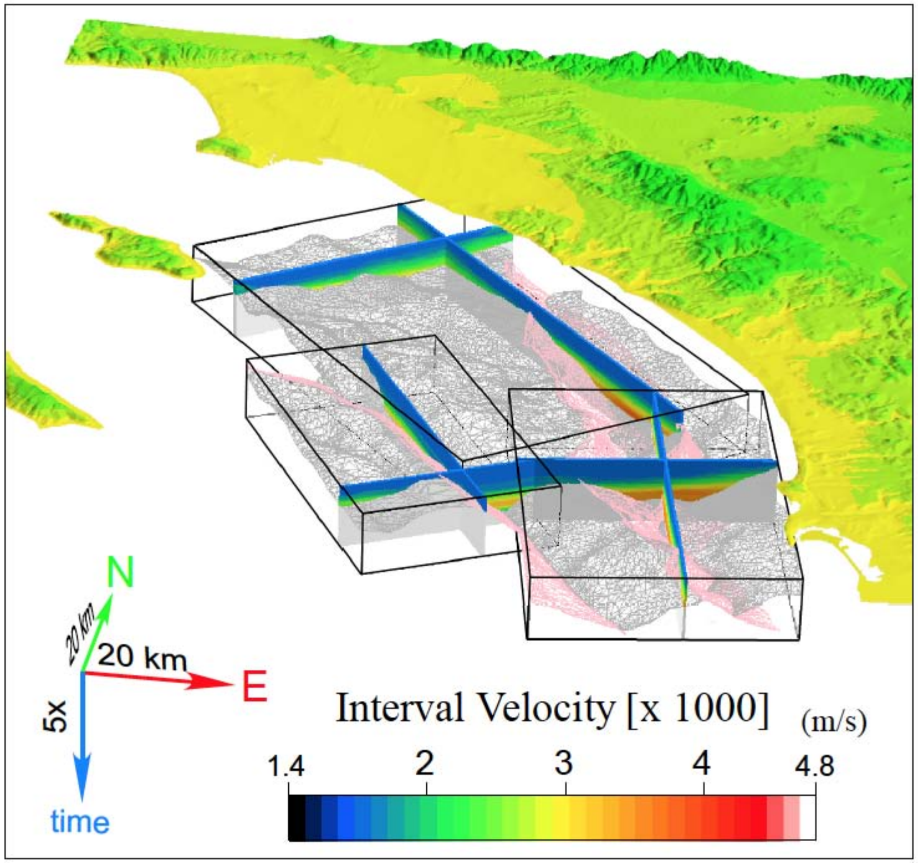


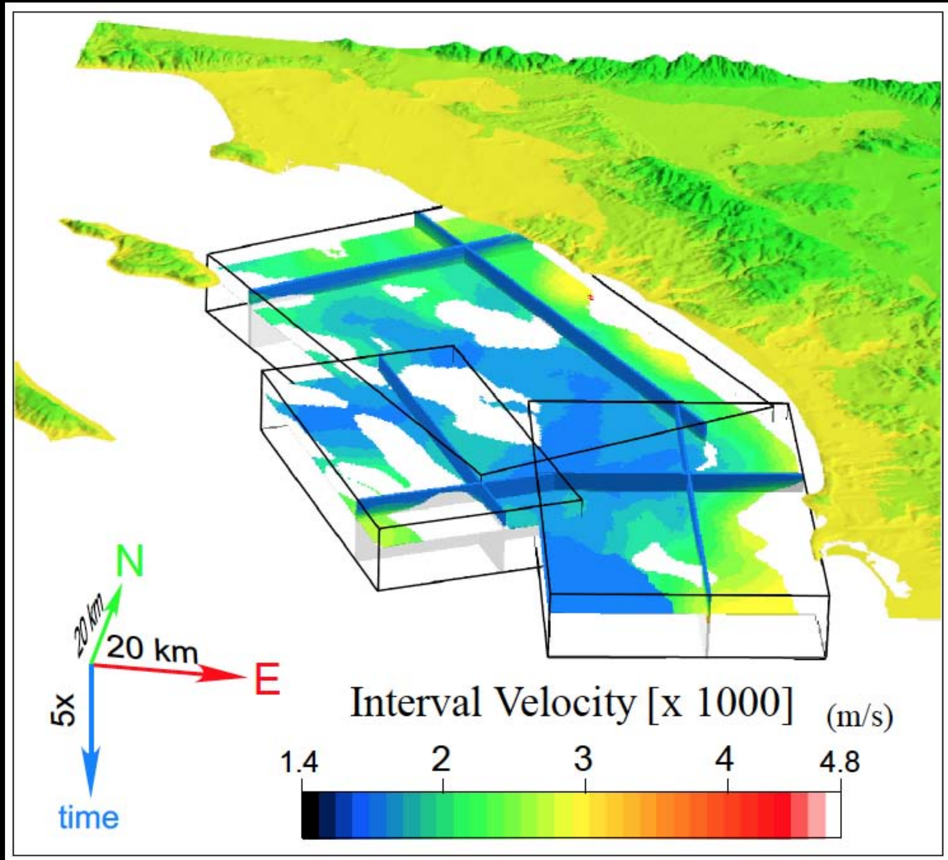
Define correlation elipsoid



Velocity parameterization through kriging

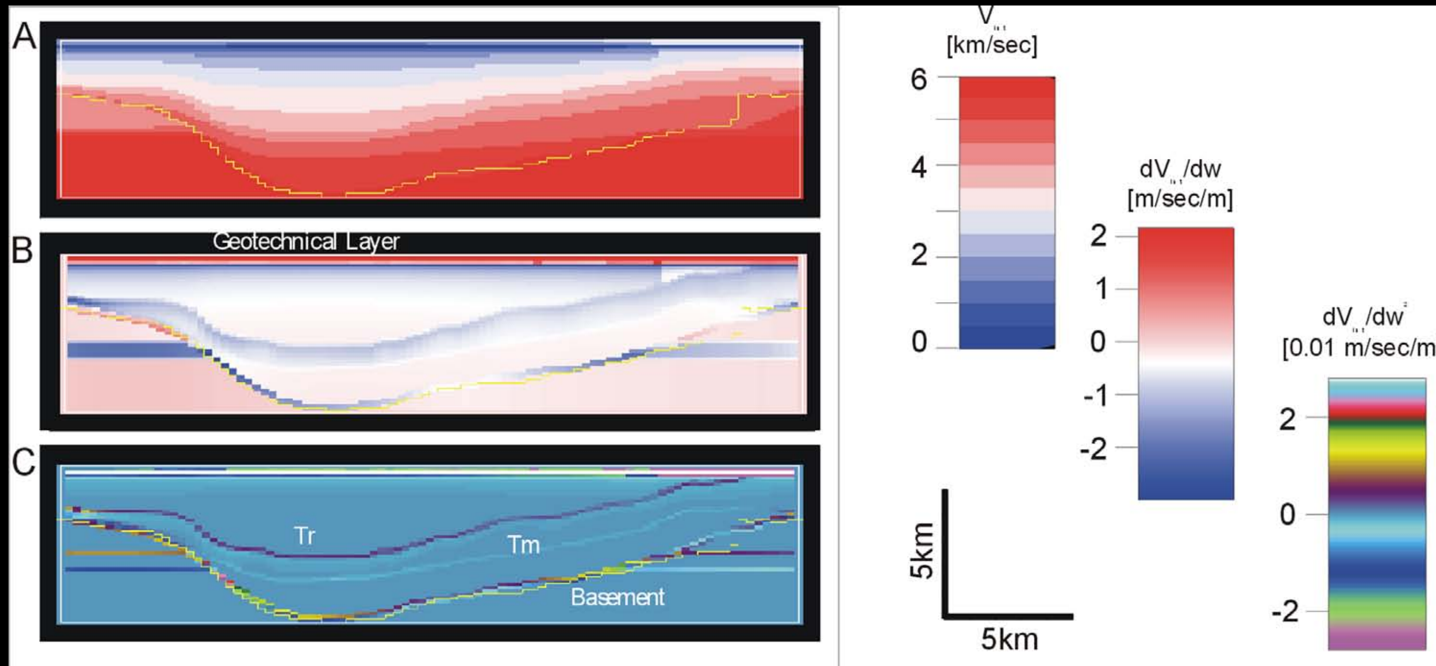
Velocity interpolation based on spatially weighted mean



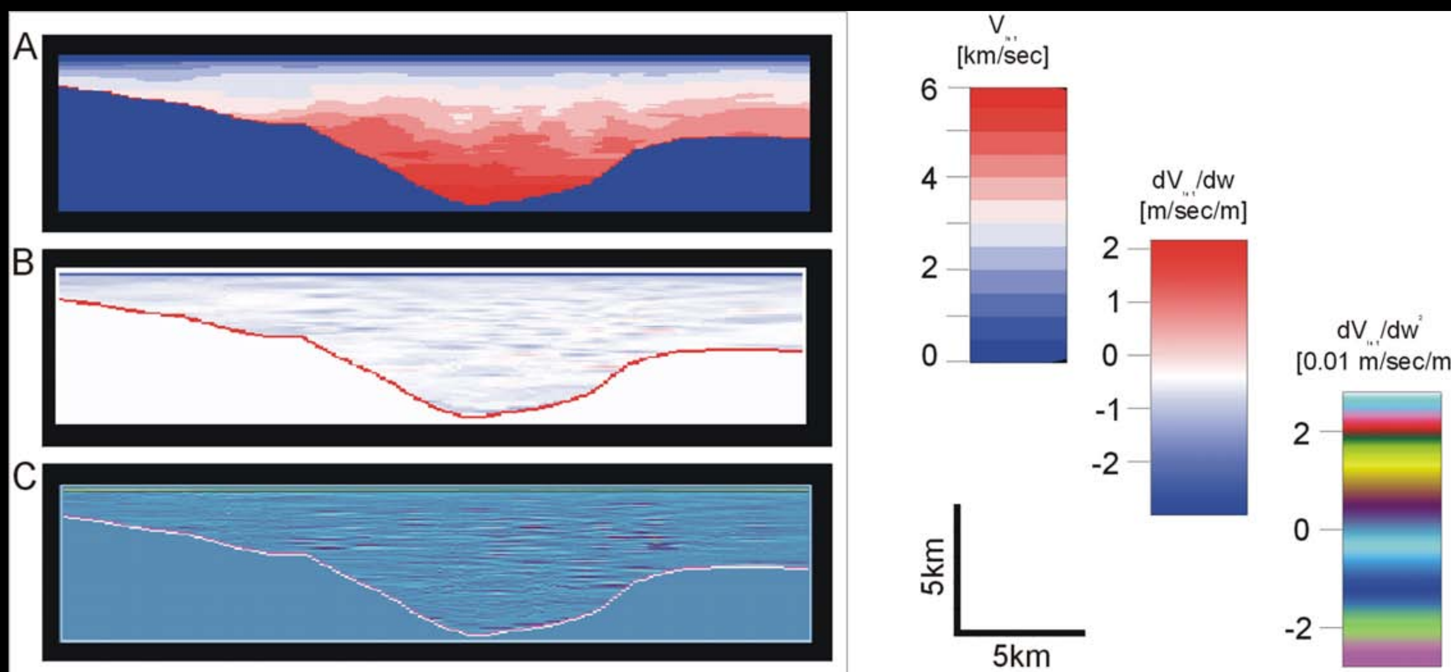


Rivero et al., 2004

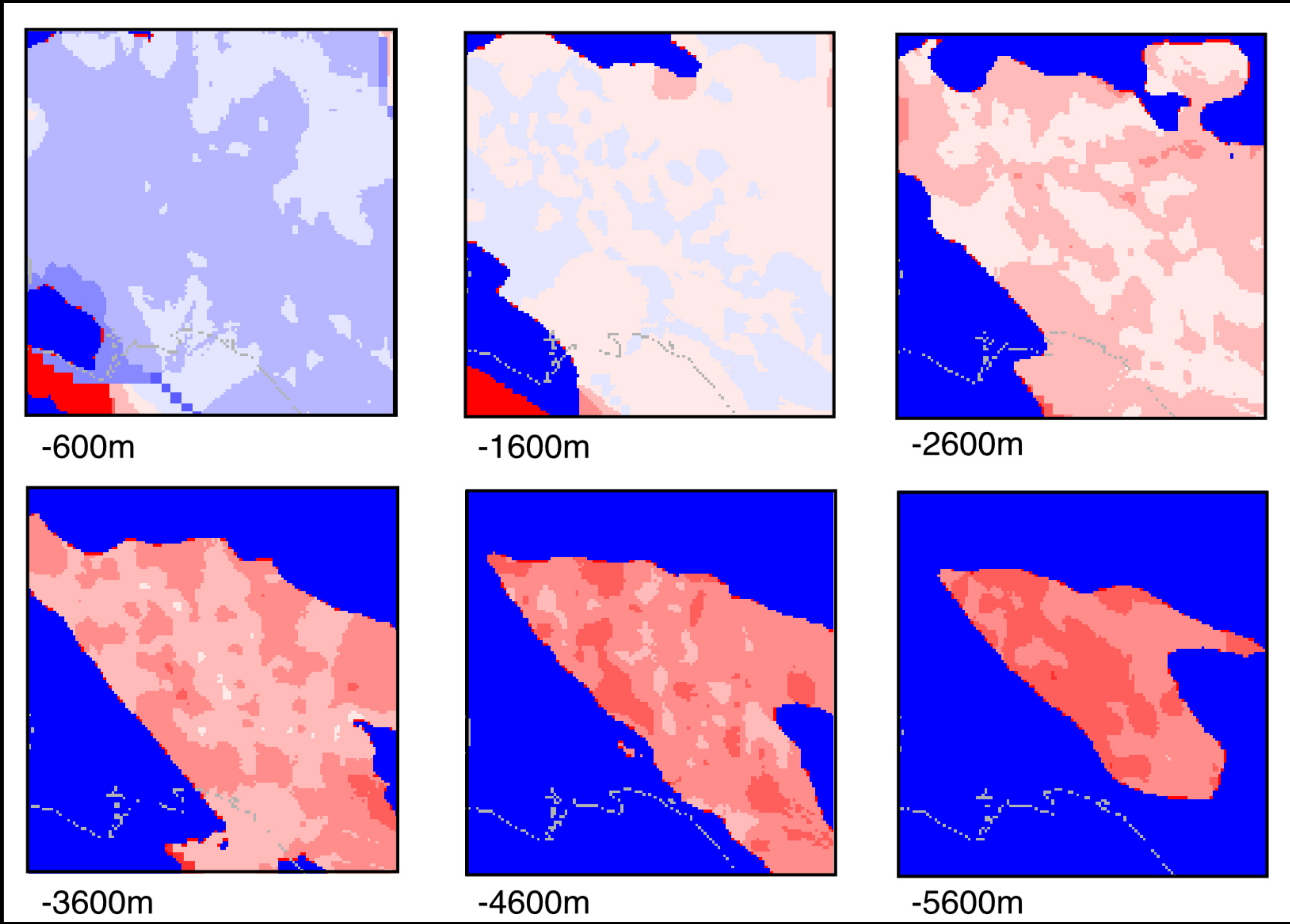
Rule-based model



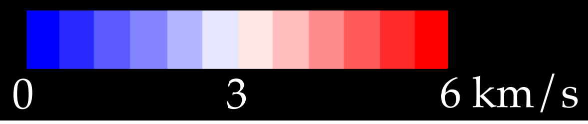
Geostatistical model



Depth slices through parameterized model

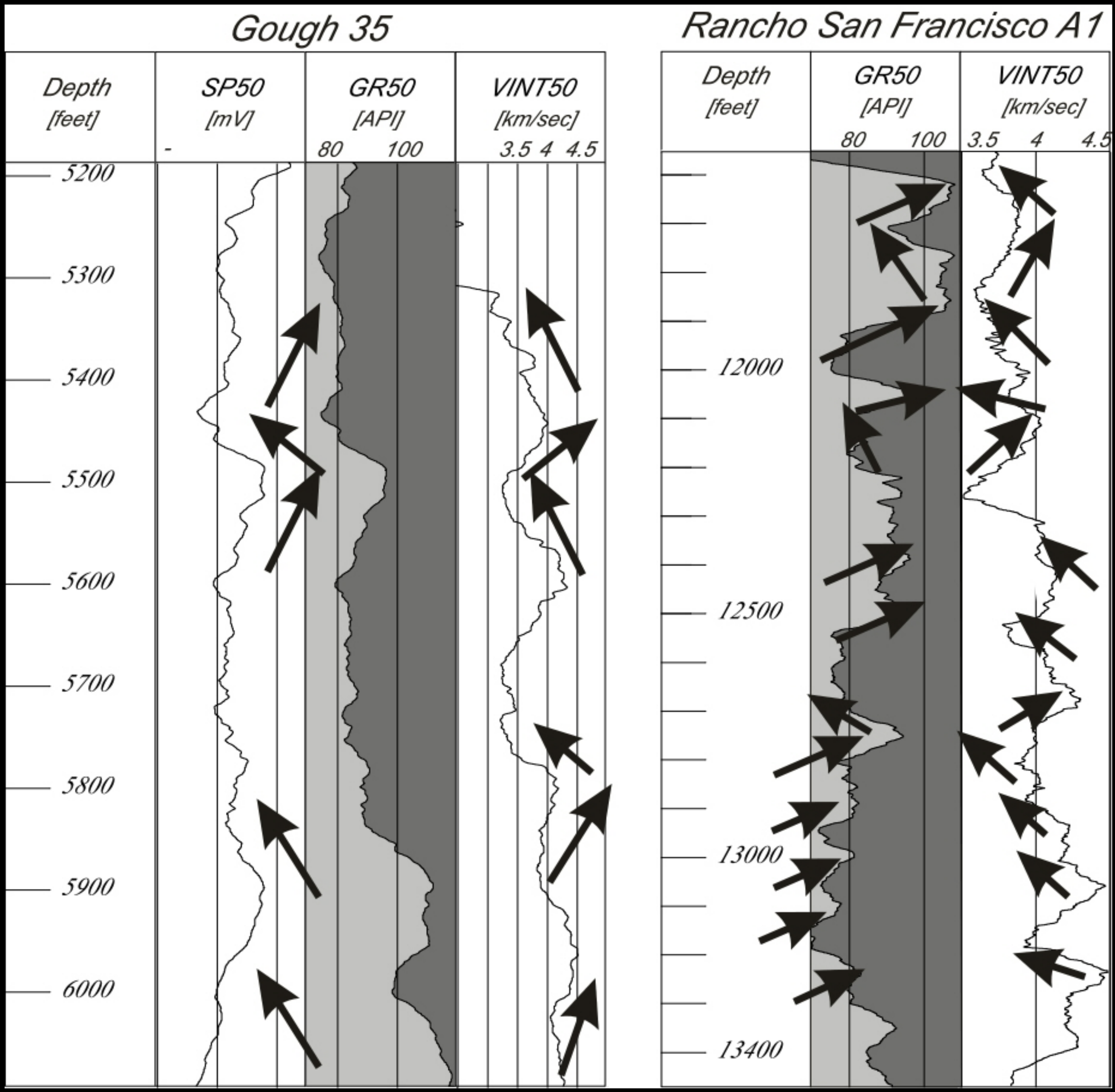


Süss & Shaw (2003)



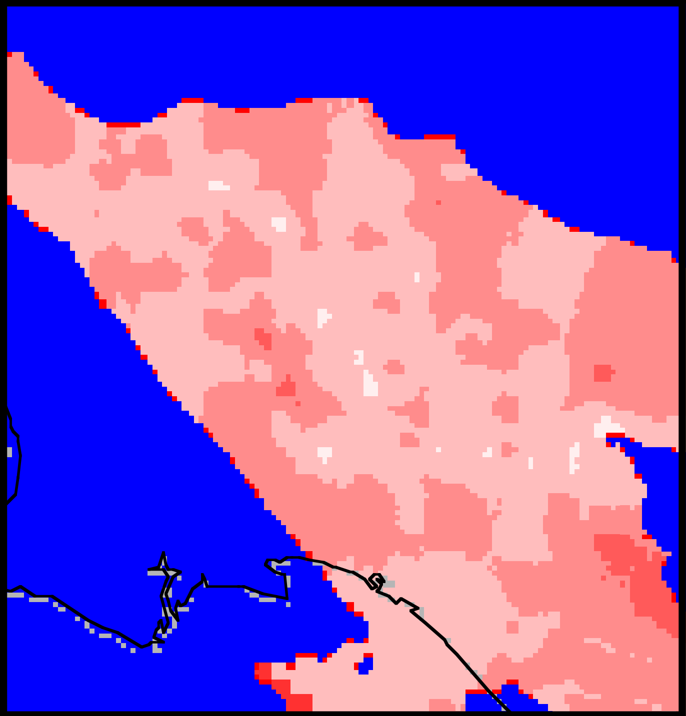
Lithologic control on velocity

- Vp low in shales
- Vp high in sands

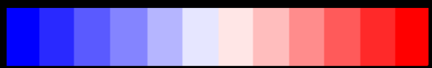


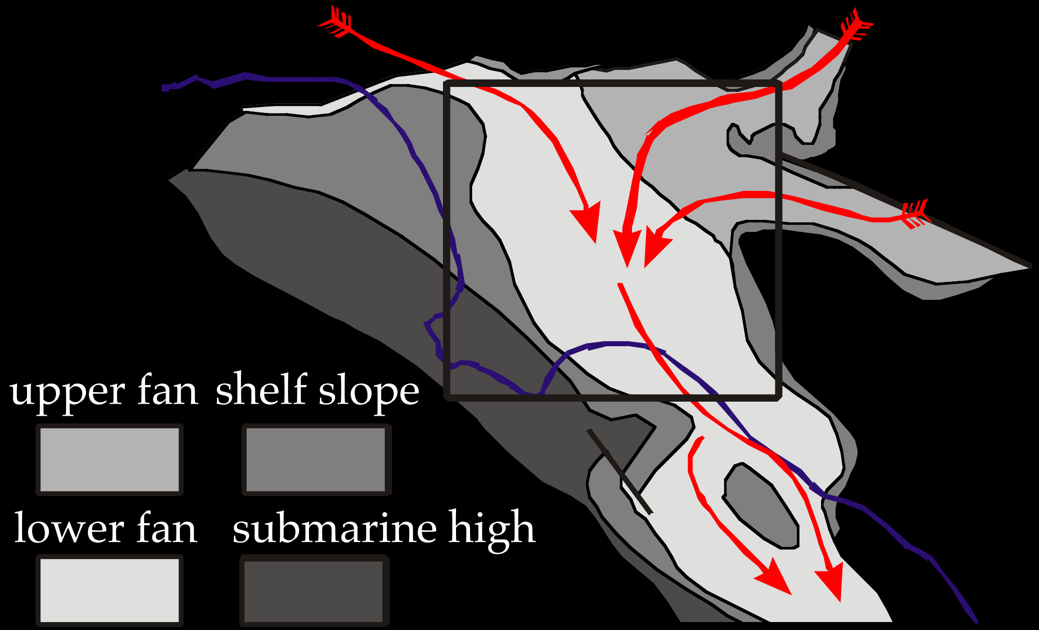
Depositional systems

Basinfloor fan deposits resolved in velocity model of the LA basin



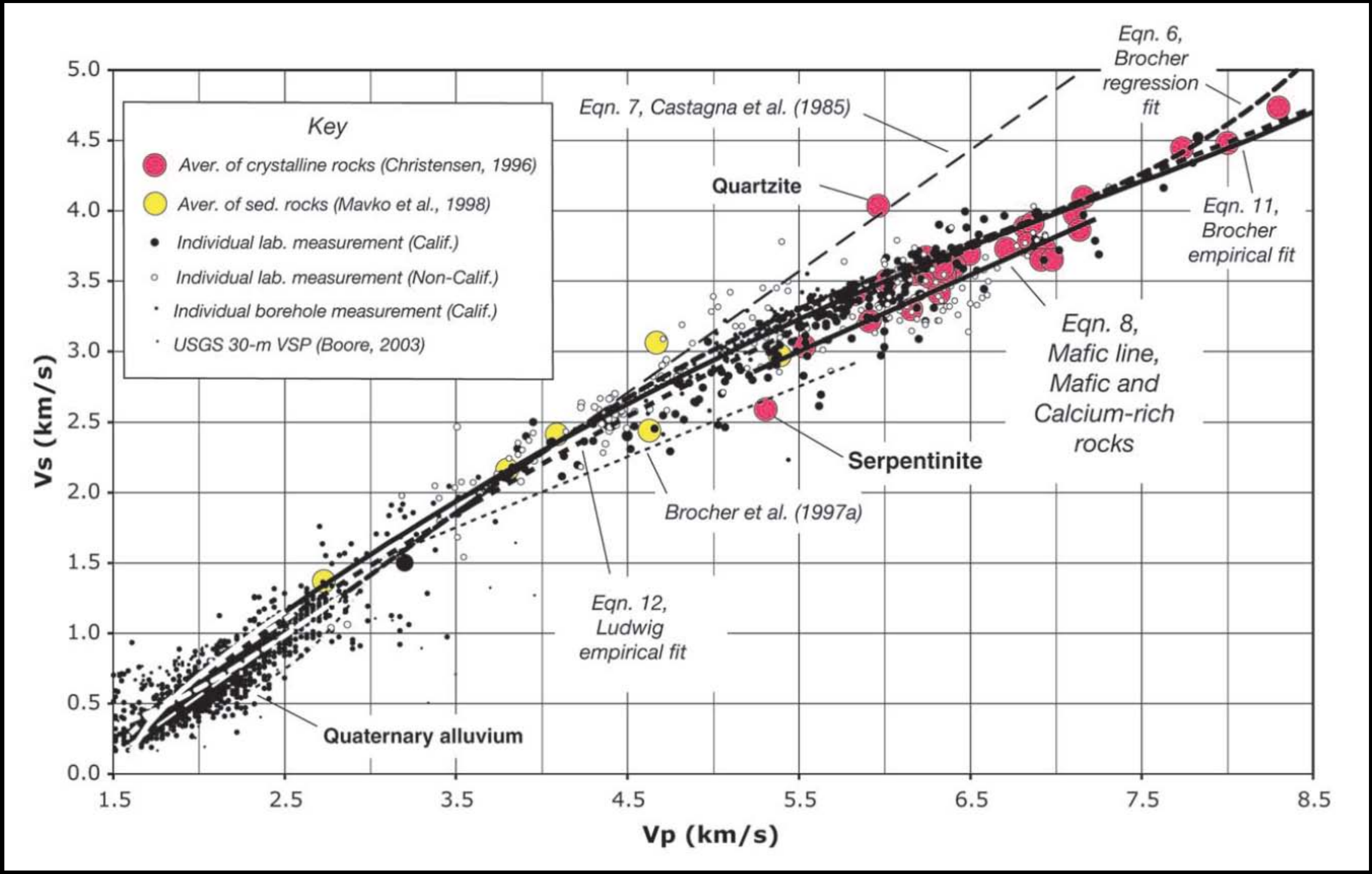
Velocity slice at 3600m



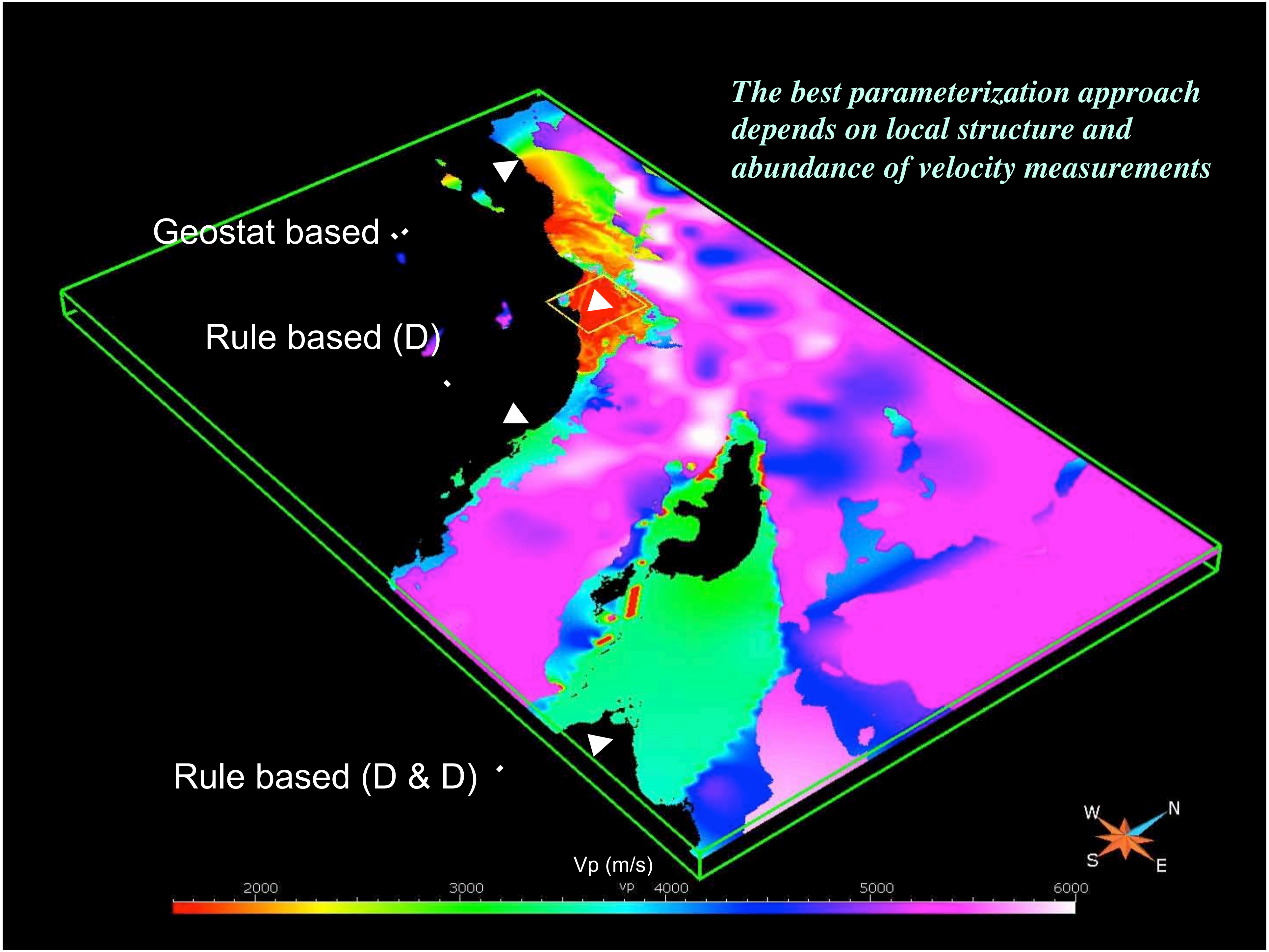


Deveoping Vs and r models for basins

Co-registered Vp and r models are developed using empirical relations among these properties

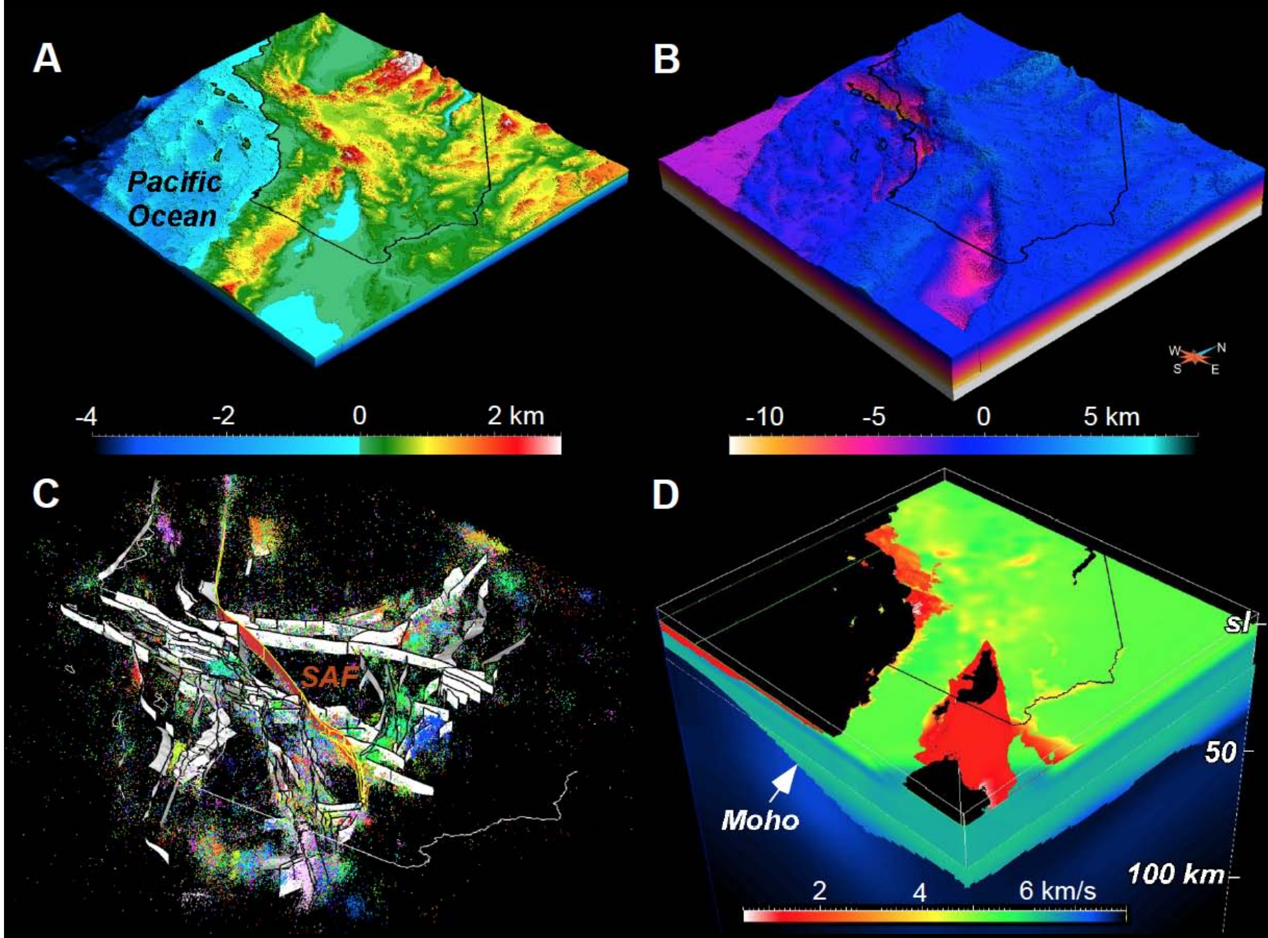


Brocher et al., 2005



The best parameterization approach depends on local structure and abundance of velocity measurements
Geostat based
Rule based (D)
Rule based (D & D)
Vp (m/s)
2000
3000
vp
4000
5000
6000
W
N
S
E

SCEC Unified Structural Representation (USR) Workflow



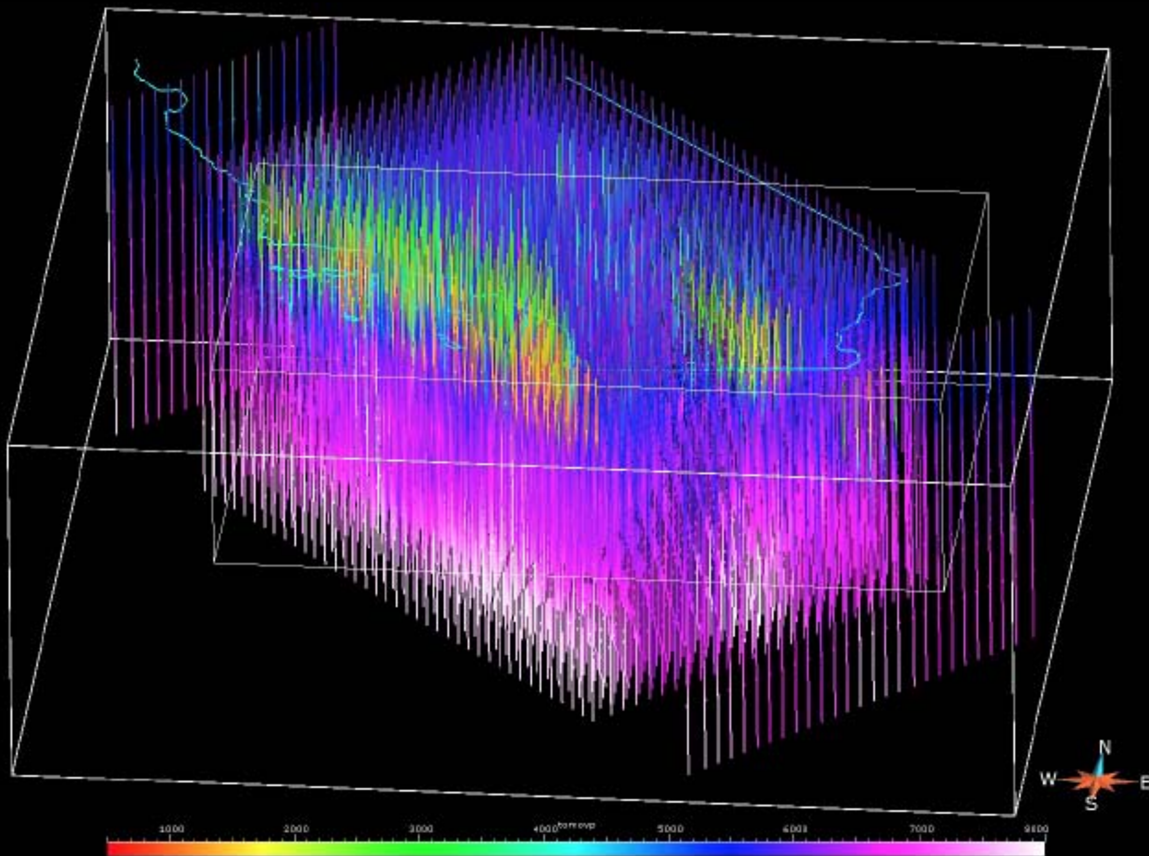
1) Definition of geological and geophysical horizons

2) Incorpration of fault locations and displacements

3) Parameterization of sediment velocities

4) Embed basins in consistent crust and upper mantle V models

Crustal models

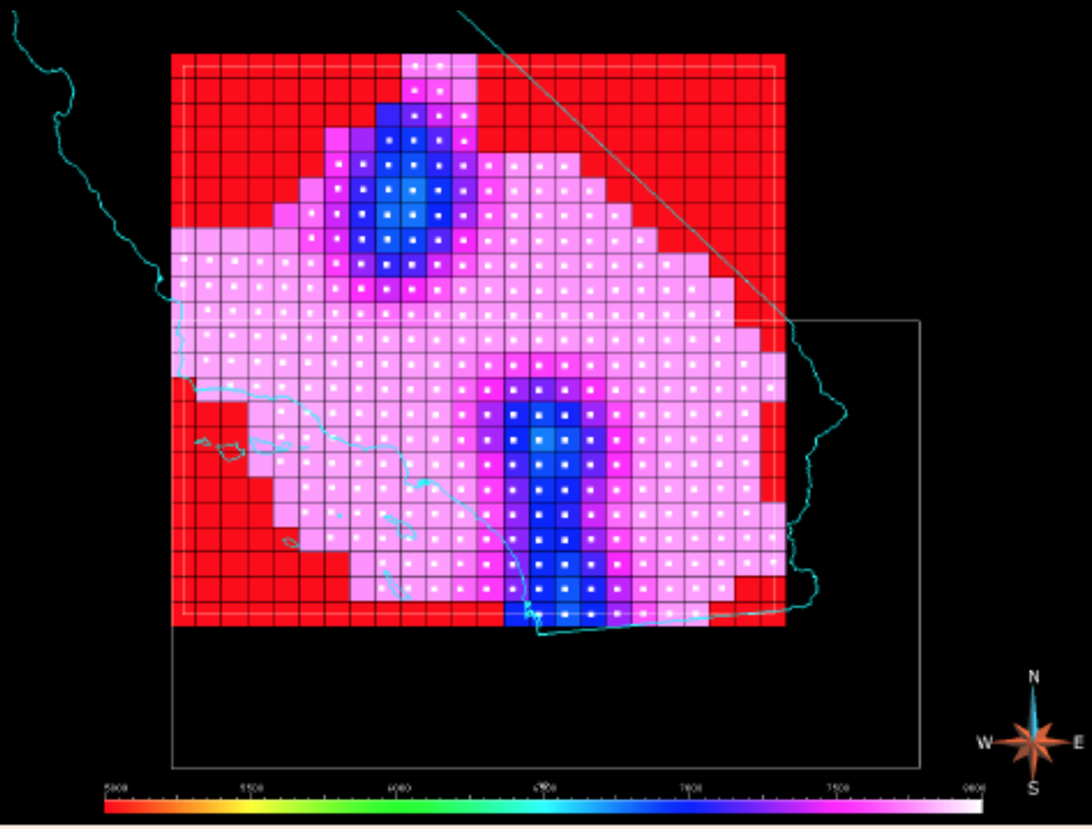


After Hauksson et al. (2000)

- To ensure internal consistency between basin and crustal velocity representations, basin structures are used as input for Vp and Vs tomographic (travel-time based) models

- Models were developed using the inversion code SIMULPS (Thurber, 1993) and travel time P and S-P picks from the Southern California Seismic Network to determine gridded Vp and Vp/Vs models with linear interpolation between adjacent nodes.

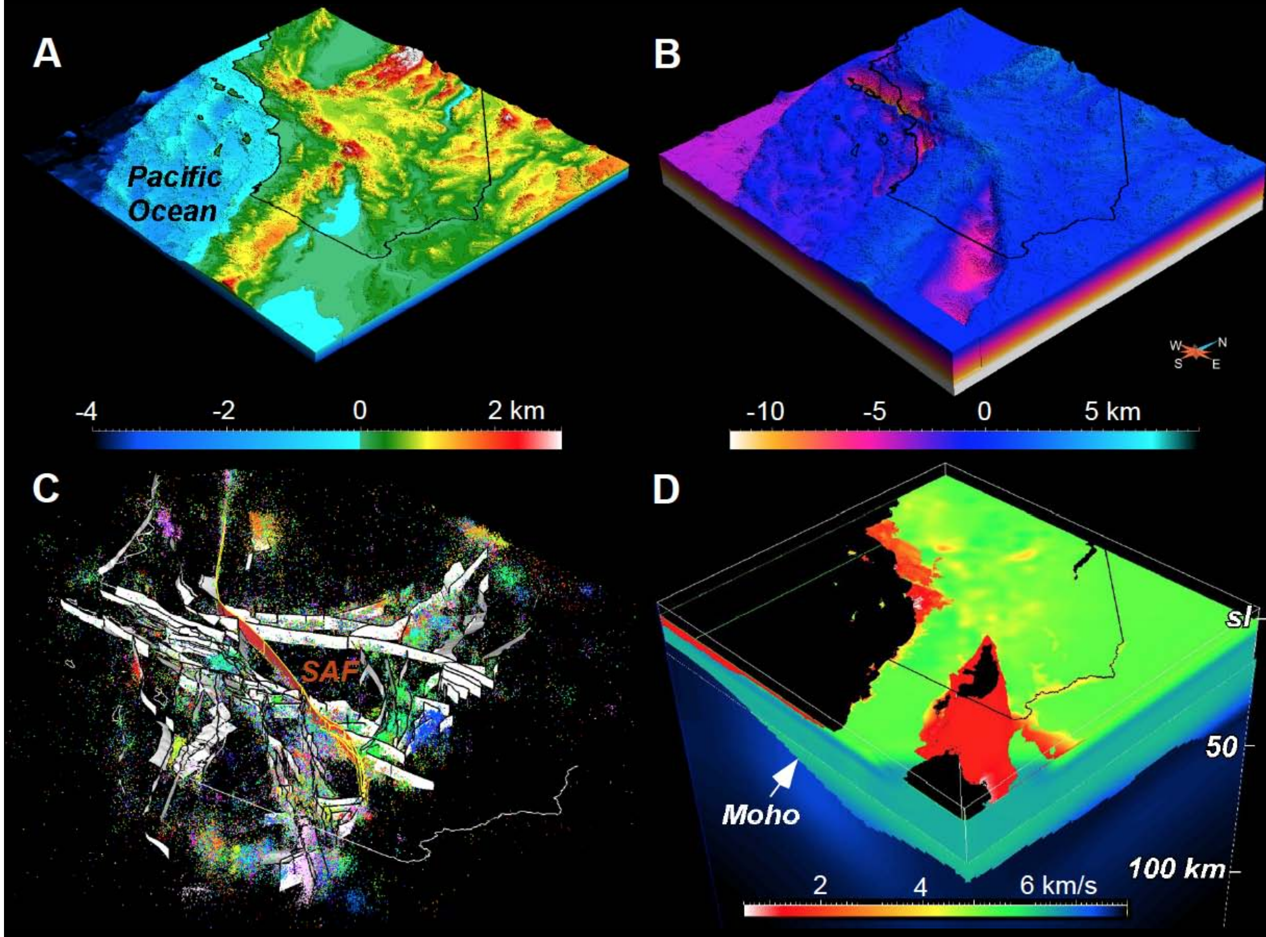
Mantle models



- Mantle structure was modeled using teleseismic surface wave data, recorded by the California Integrated Seismic Network (CISN)
- 114 large earthquakes (M>6.0) to derive phase velocity variations
- Basin and crustal models were used as inputs
- Moho surface defined boundary between crust and upper mantle models

After Tanimoto (UCSB)

SCEC Unified Structural Representation (USR) Workflow



1) **Definition of geological and geophysical horizons**

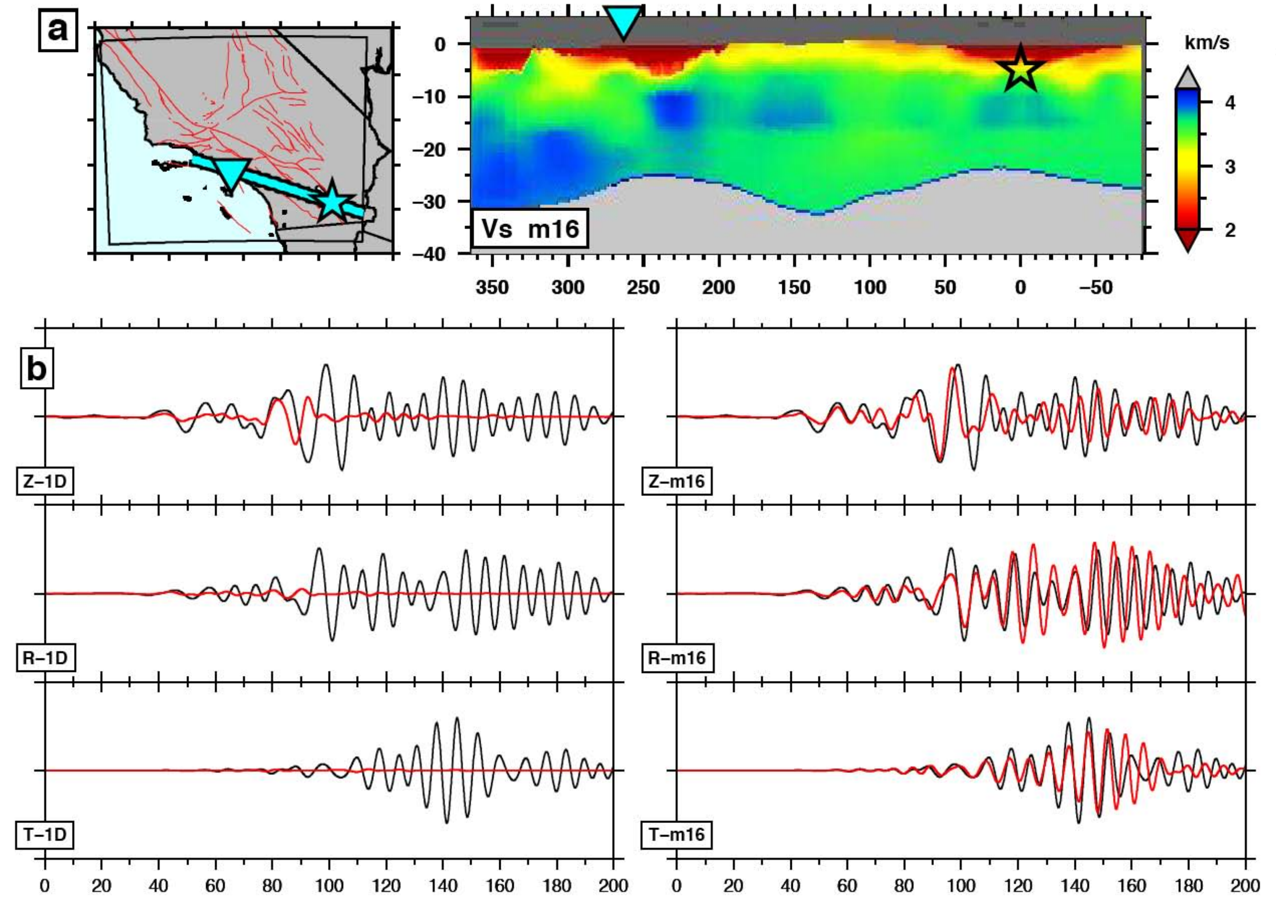
2) **Incorpration of fault locations and displacements**

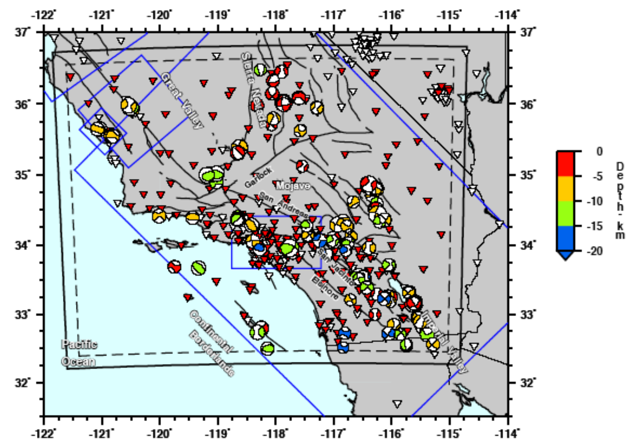
3) **Parameterization of sediment velocities**

4) **Embed basins in crust and upper mantle V models**

5) **Iteration of velocity models using 3D waveform tomography**

3D adjoint waveform tomography updates



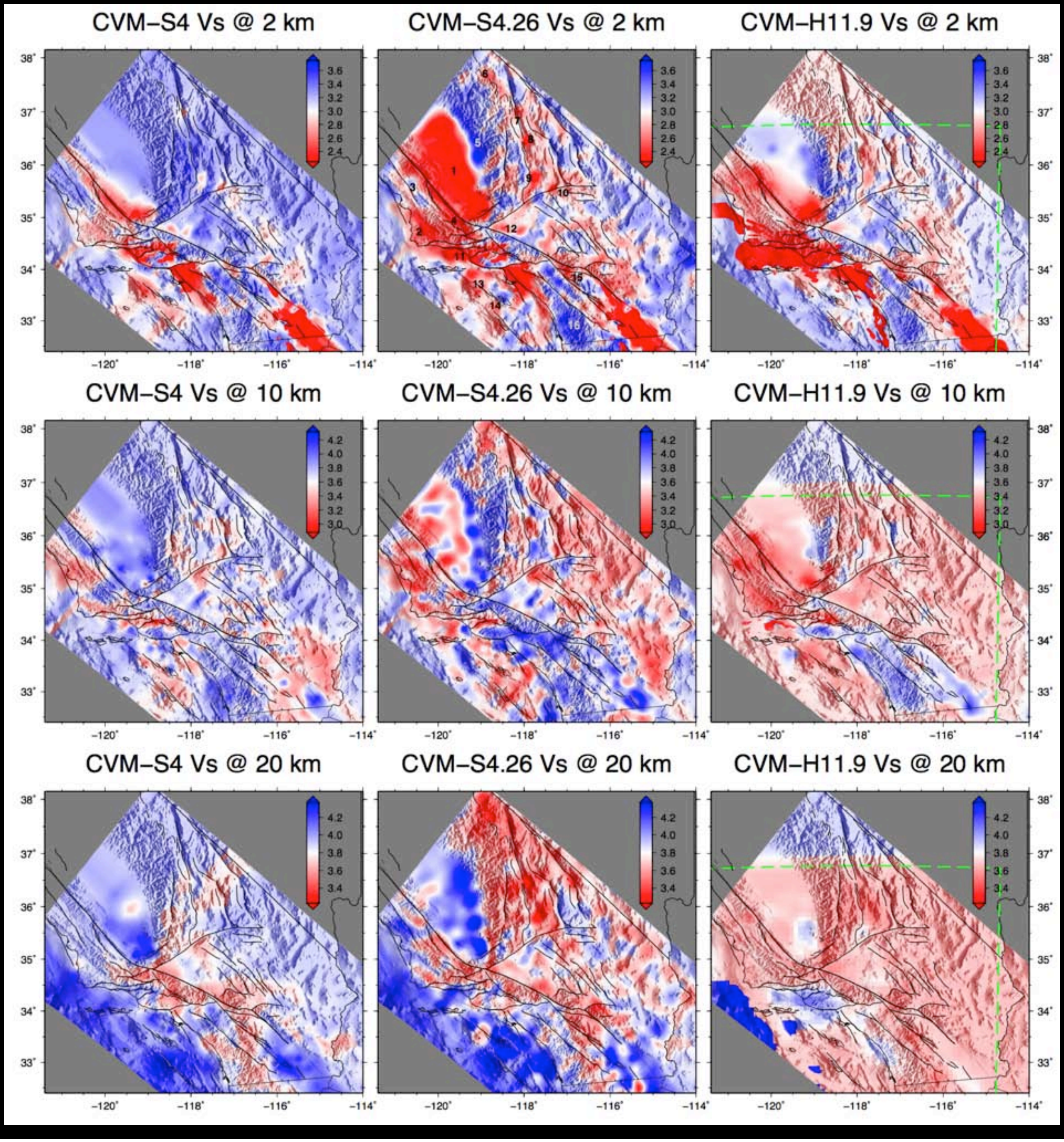


Full inversion uses more than 200 events, requiring 6800 wavefield simulations, implemented in 16 tomographic iterations.

6–30 s period

Tape et al., (2009)

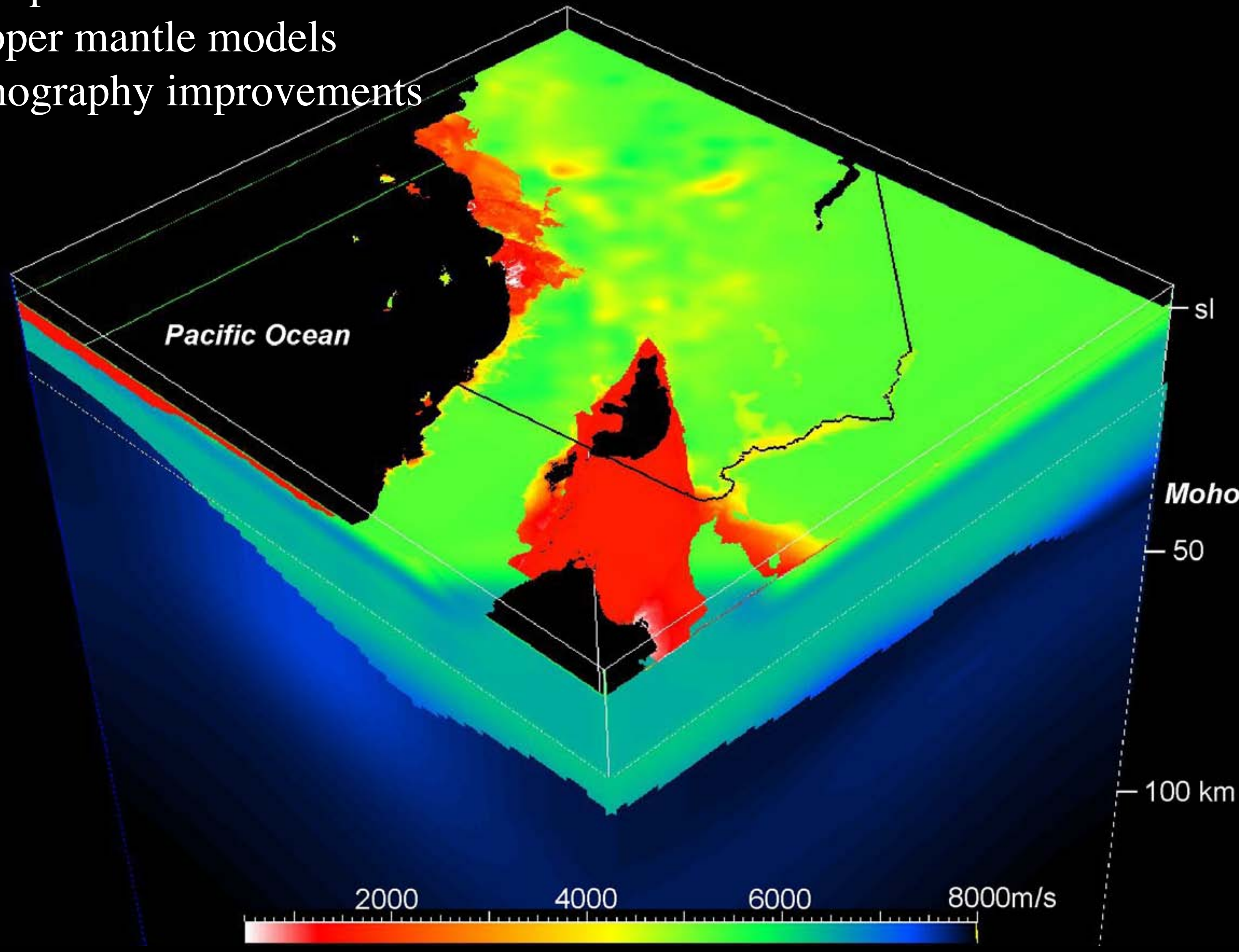
3D waveform tomography (F3DT)



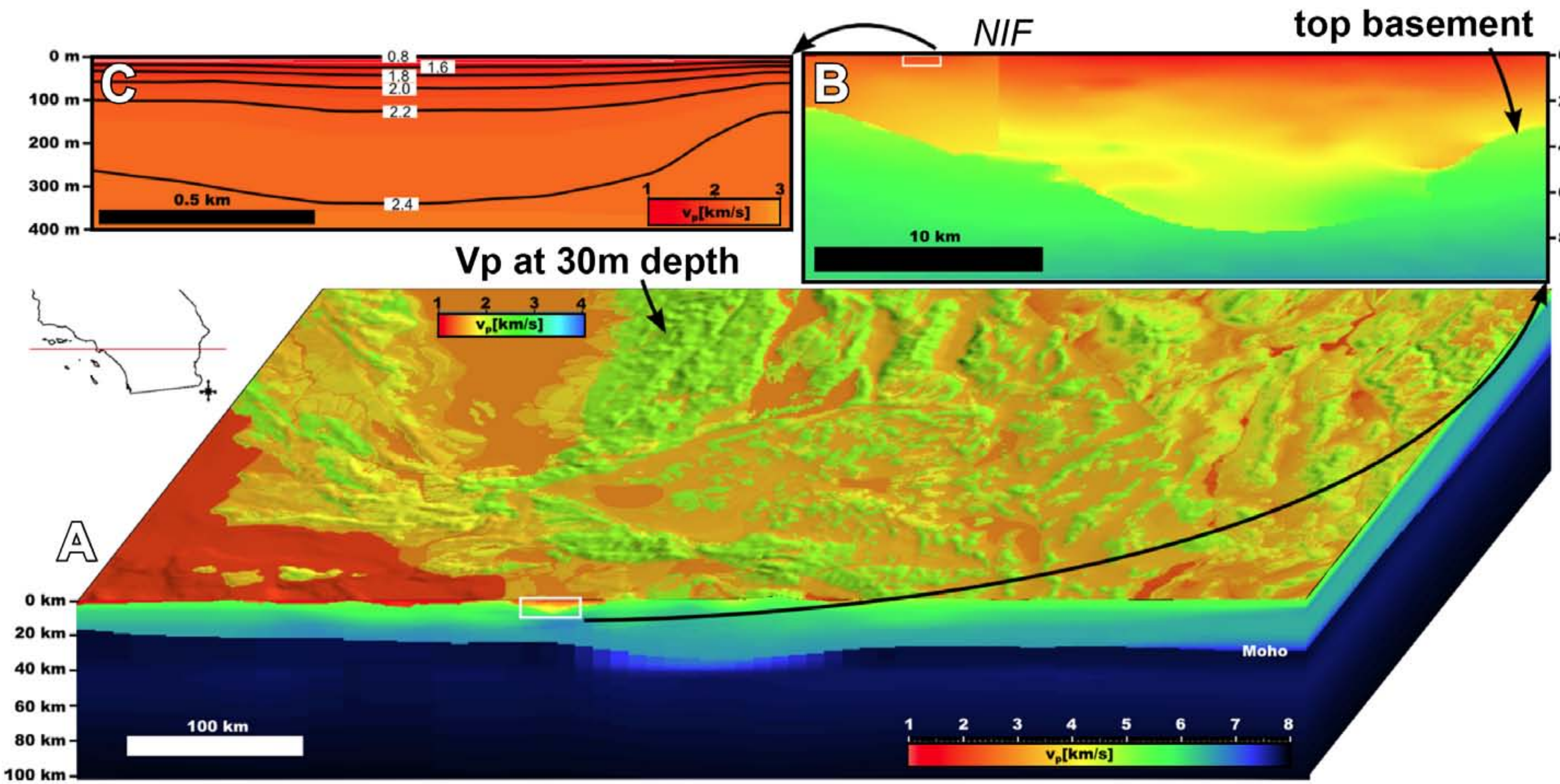
Lee, E.-J., P. Chen, T. H. Jordan, P. B. Maechling, M. A. M. Denolle, and G. C. Beroza (2014), Full-3-D tomography for crustal structure in Southern California based on the scattering-integral and the adjoint-wavefield methods, *J. Geophys. Res. Solid Earth*, 119, doi:10.1002/2014JB011346.

SCEC USR Components

- Basin structures
- Crustal tomographic models
- Teleseismic upper mantle models
- Waveform tomography improvements



Geotechnical Layer (GTL)



Shaw et al., (2013)

- GTL's are shallow (< 300 m) velocity descriptions that are necessary for many local seismological and engineering applications.
- The USR/CVM has an optional GTL overlay based on Vs30 measurements.

Geotechnical Layer (GTL)

$$V_S(z) = f(z)V_{ST} + g(z)V_{S30}$$

$$V_P(z) = f(z)V_{PT} + g(z)P(V_{S30})$$

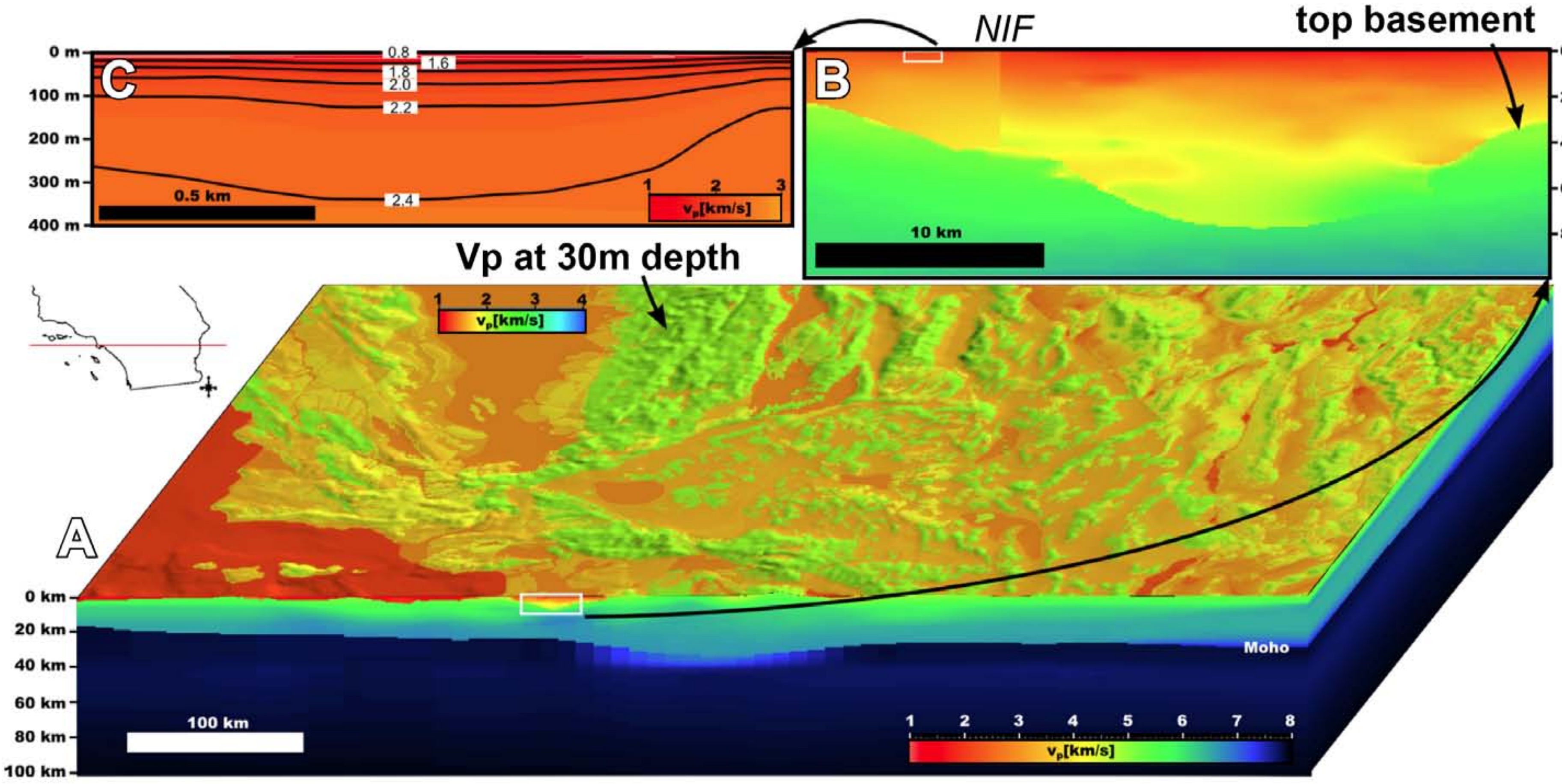
Where **z'** is depth, V_{ST} and V_{PT} are S- and P-wave velocities extracted from the crustal velocity model at depth z_T, P () is the Brocher (2005) P-wave velocity scaling law, and:

$$z = z'/z_T$$

$$f(z) = z + b(z - z^2)$$

$$g(z) = a - az + c(z^2 + 2\,z - 3z)$$

Geotechnical Layer (GTL)

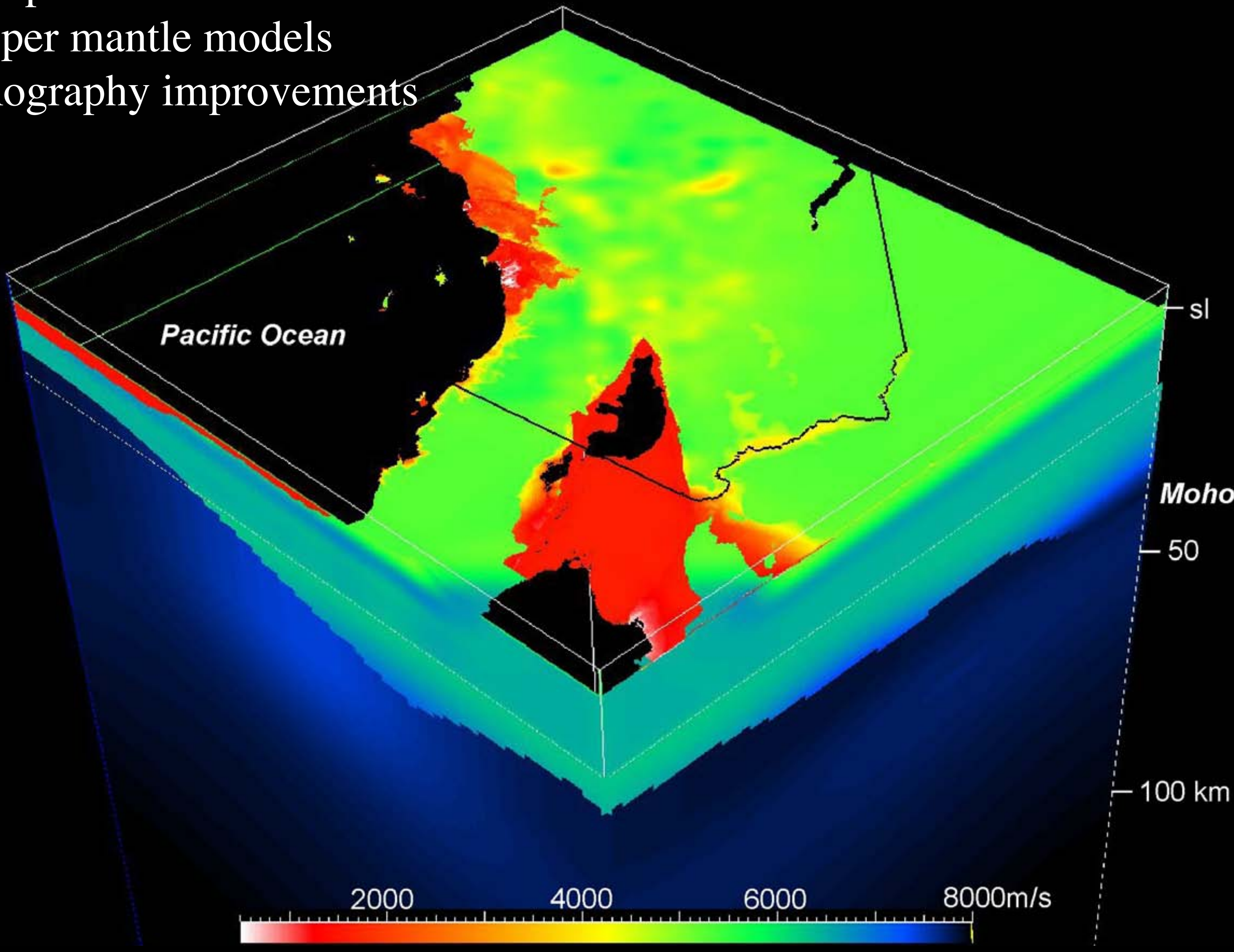


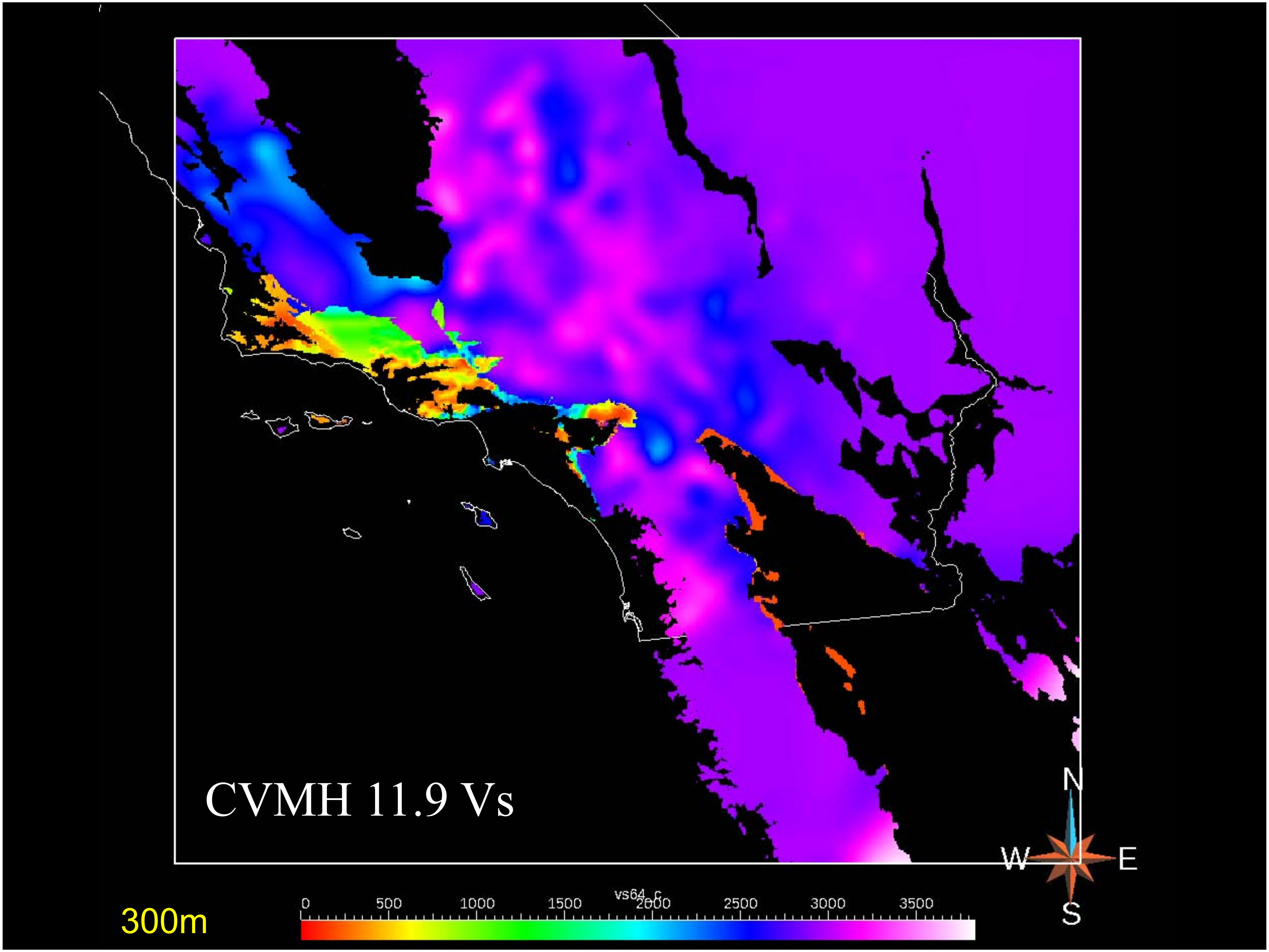
Shaw et al., (2013)

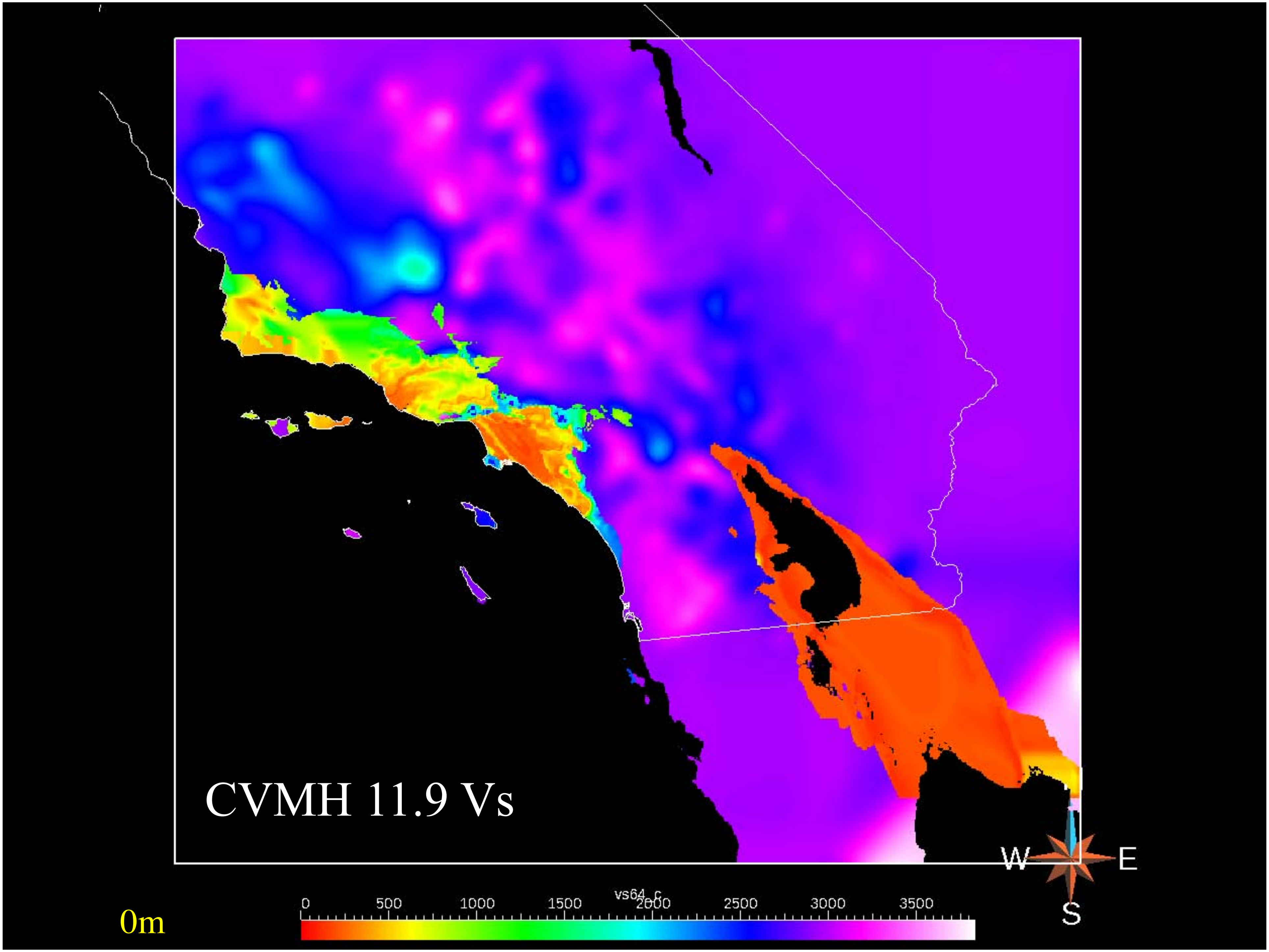
- This process ensure smooth transitions between GTL and underlying model components

SCEC USR Components

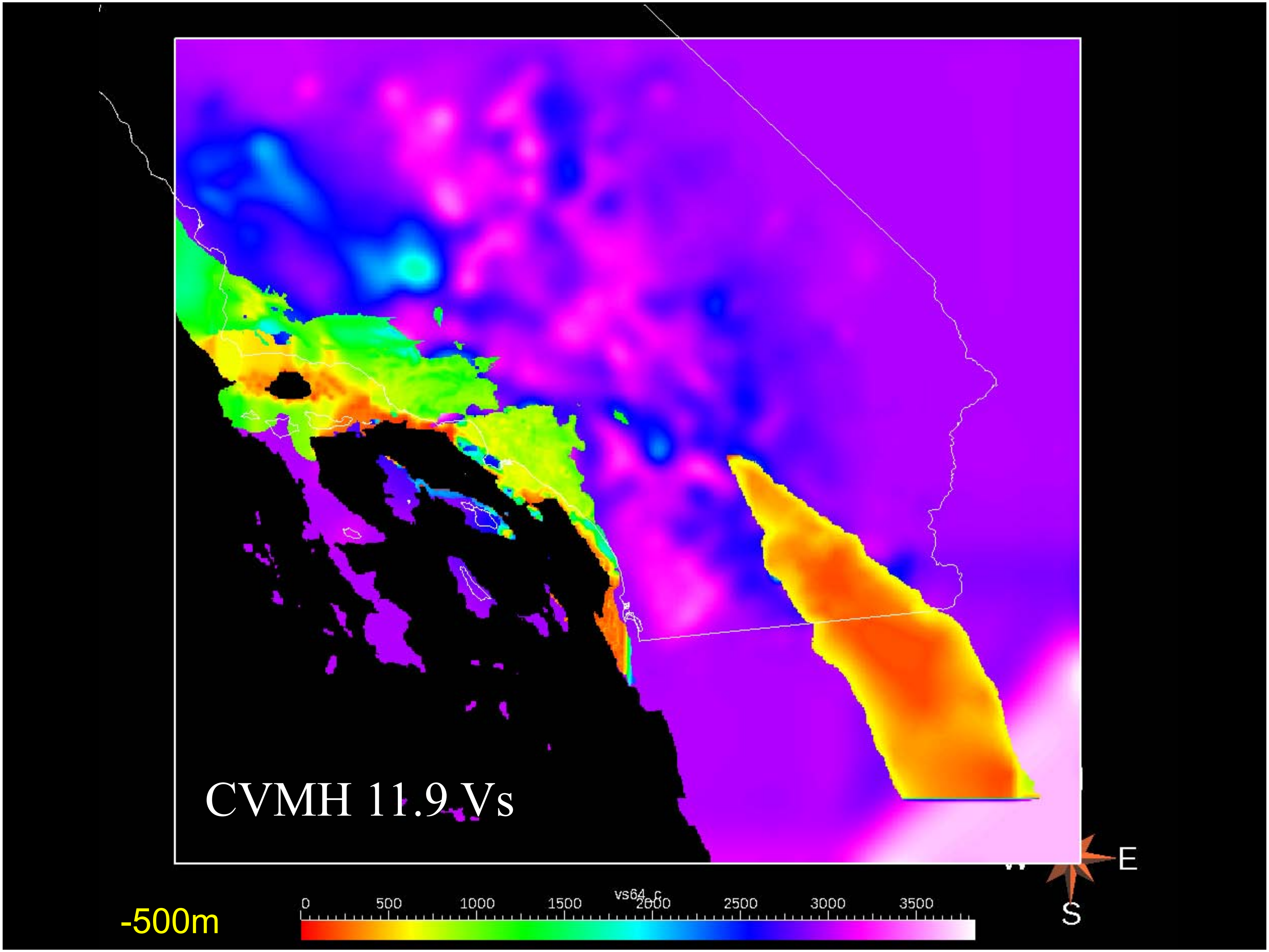
- Basin structures
- Crustal tomographic models
- Teleseismic upper mantle models
- Waveform tomography improvements
- GTL

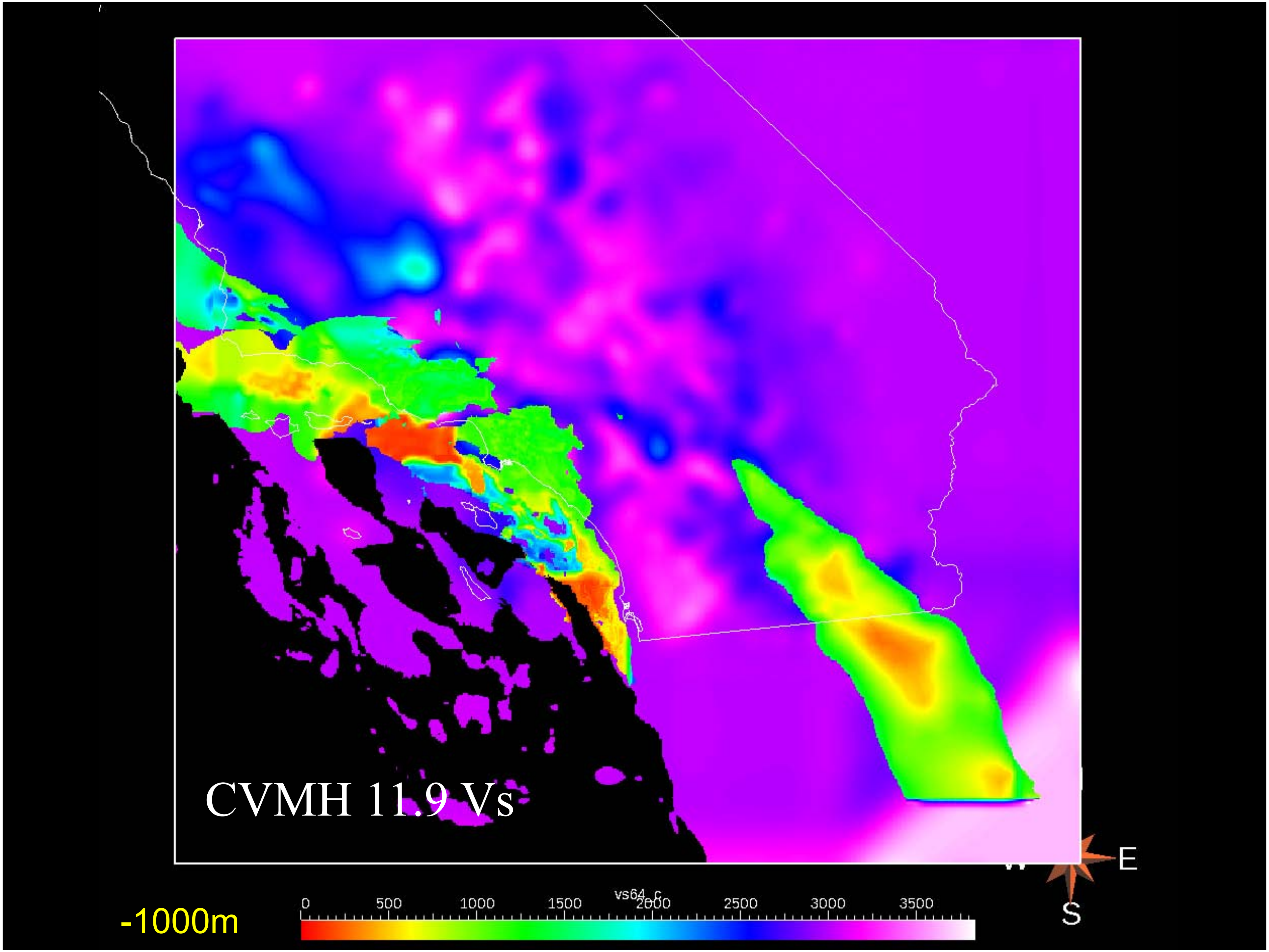


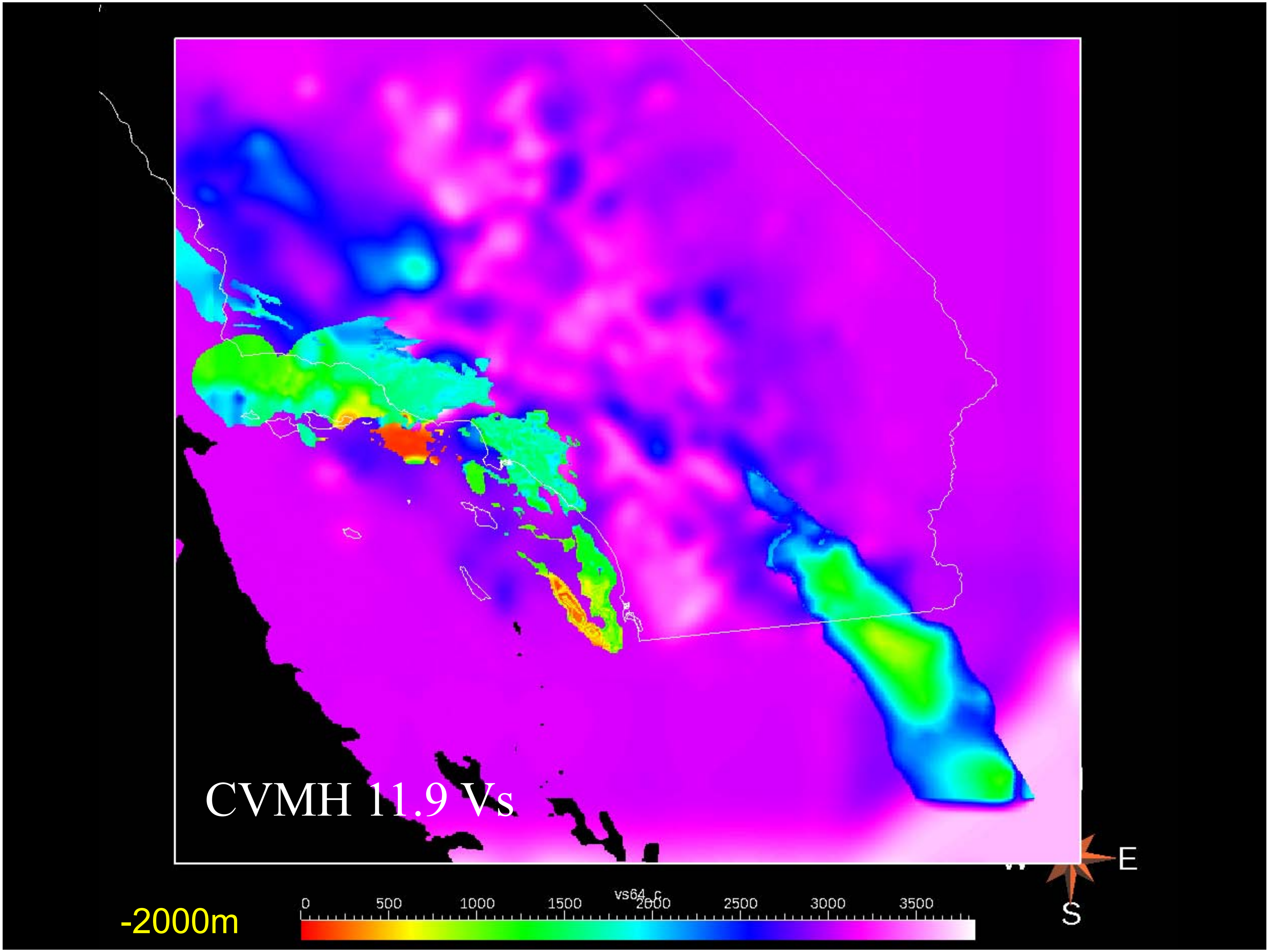

CVMH 11.9 Vs
N
W
E
S
vs64_c
0
500
1000
1500
2000
2500
3000
3500
300m



CVMH 11.9 Vs
W
E
S
vs64_c
0
500
1000
1500
2000
2500
3000
3500
0m


CVMH 11.9 Vs
-500m
vs64_c
0 500 1000 1500 2000 2500 3000 3500
E
S


CVMH 11.9 Vs
-1000m
vs64_c
0
500
1000
1500
2000
2500
3000
3500
E
S


CVMH 11.9 Vs
-2000m
vs64_c
0
500
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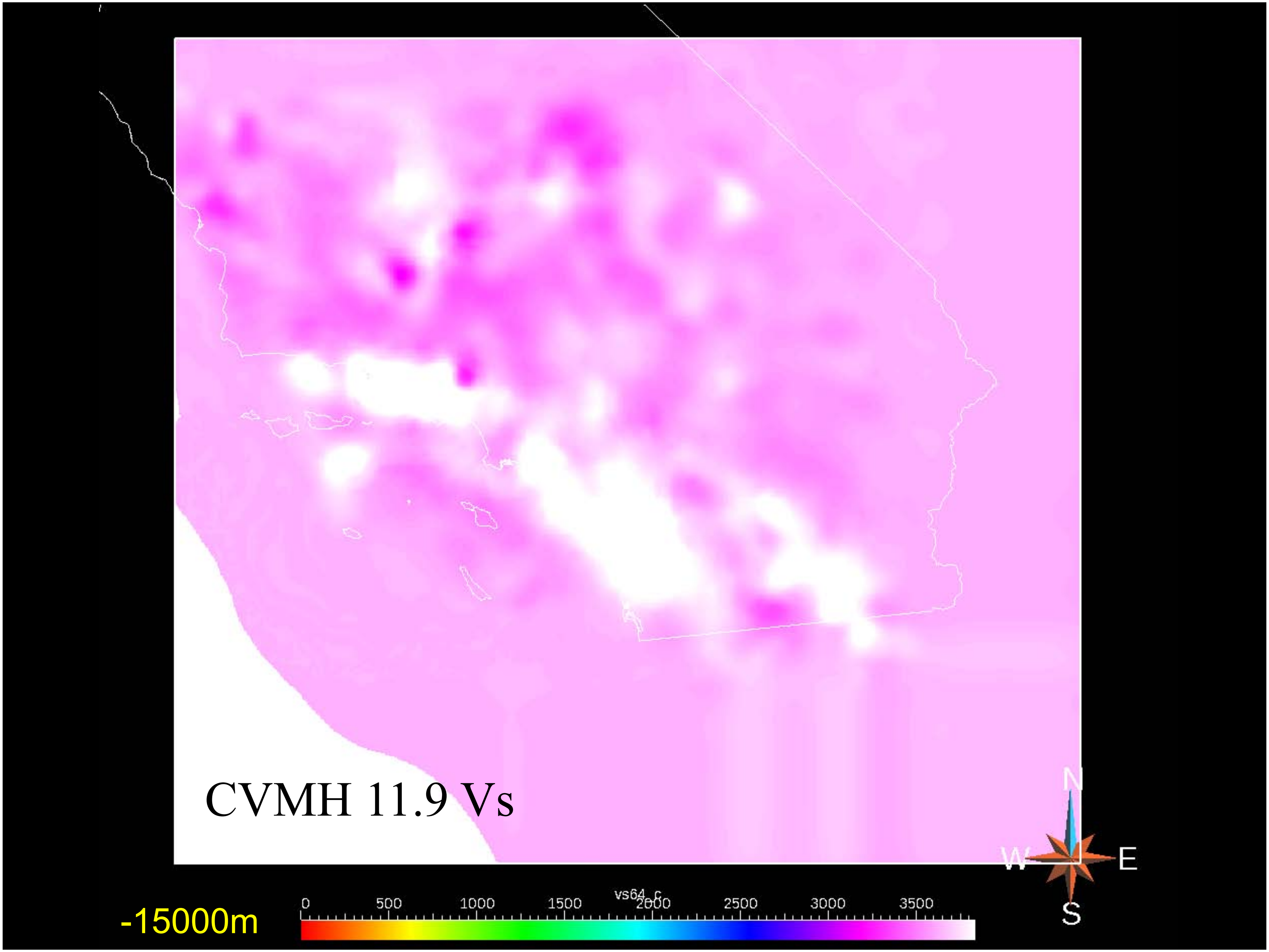
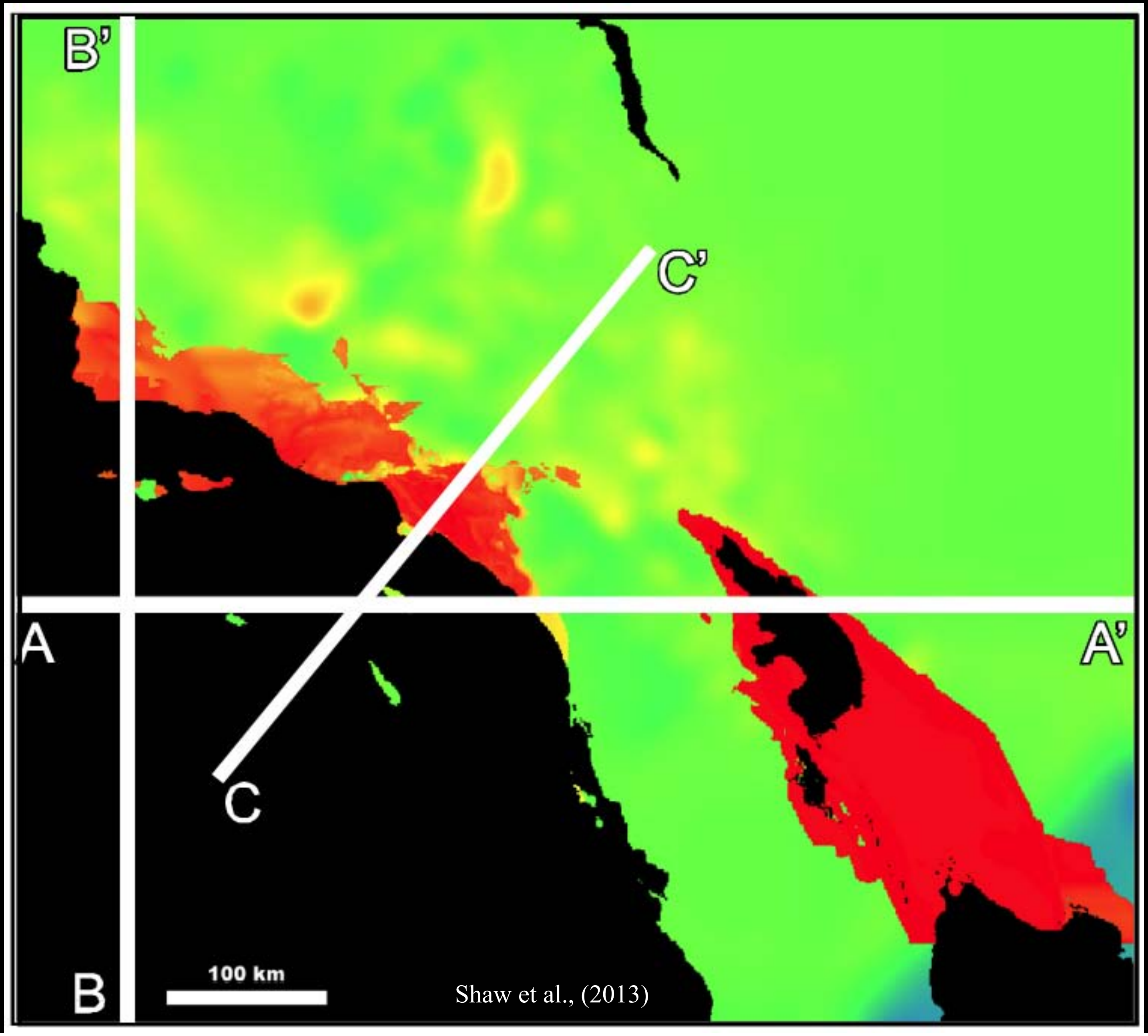
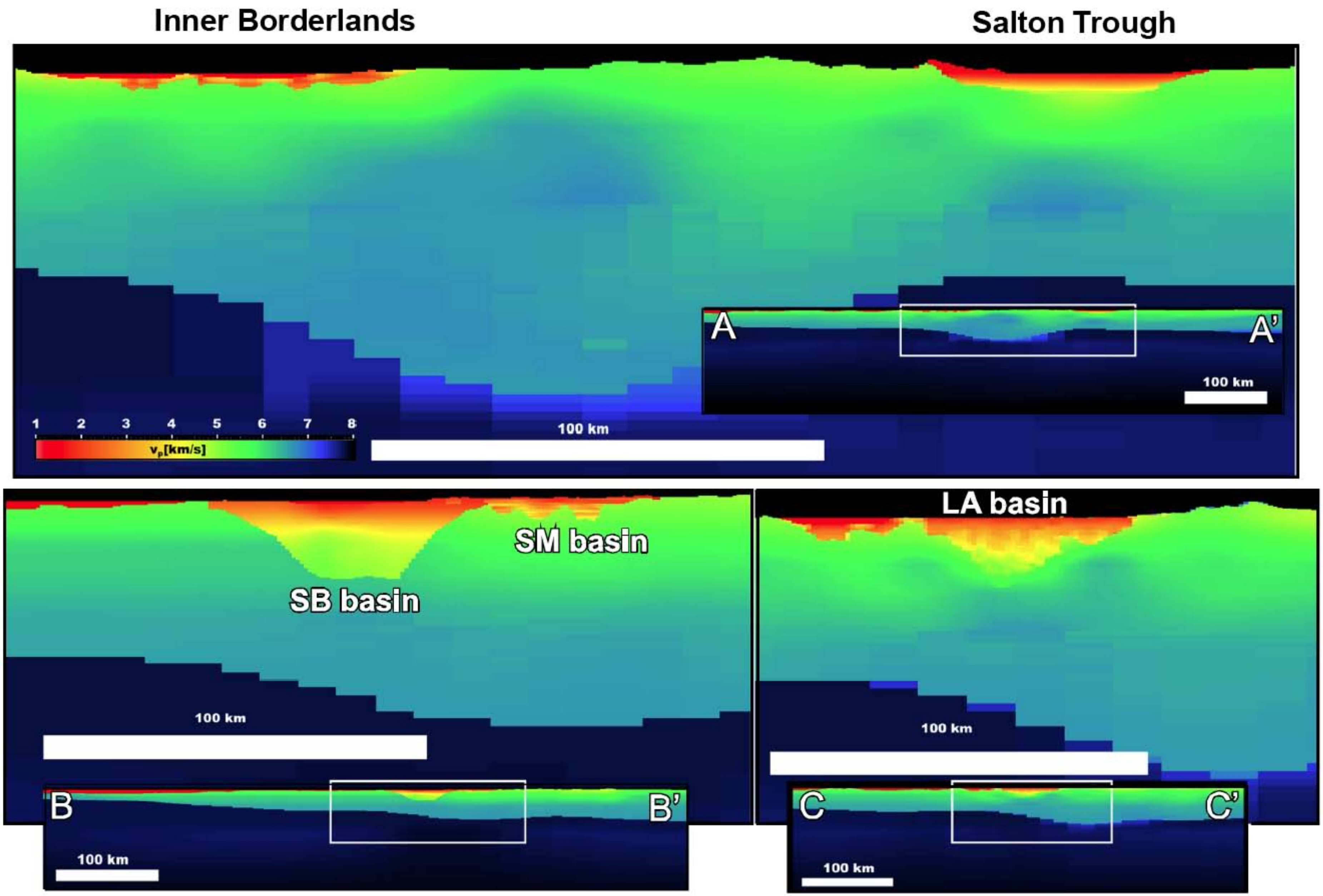
3500
E
S


CVMH 11.9 Vs
N
W
E
S
-15000m
vs64_c
0
500
1000
1500
2000
2500
3000
3500

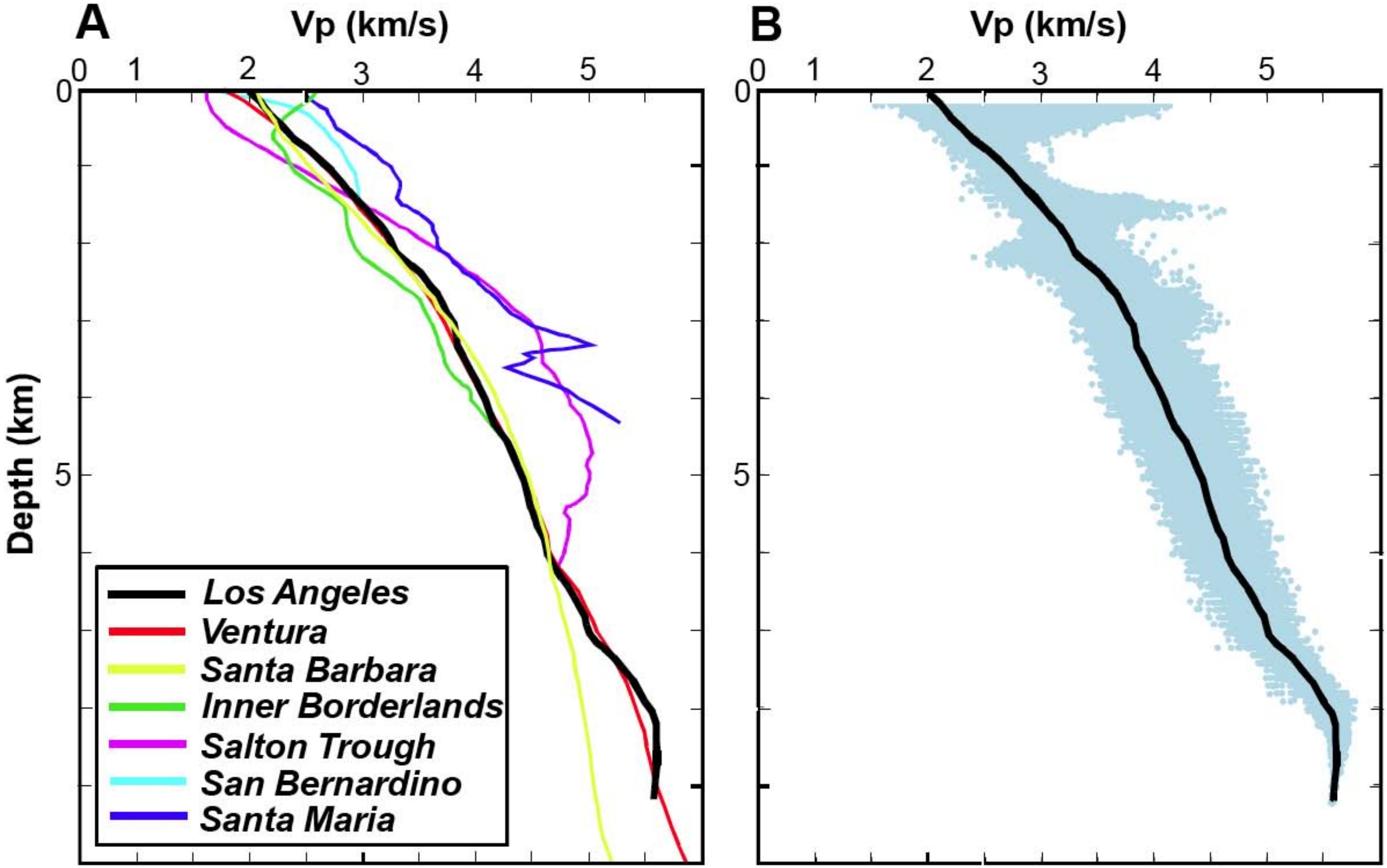
SCEC USR - CVMH





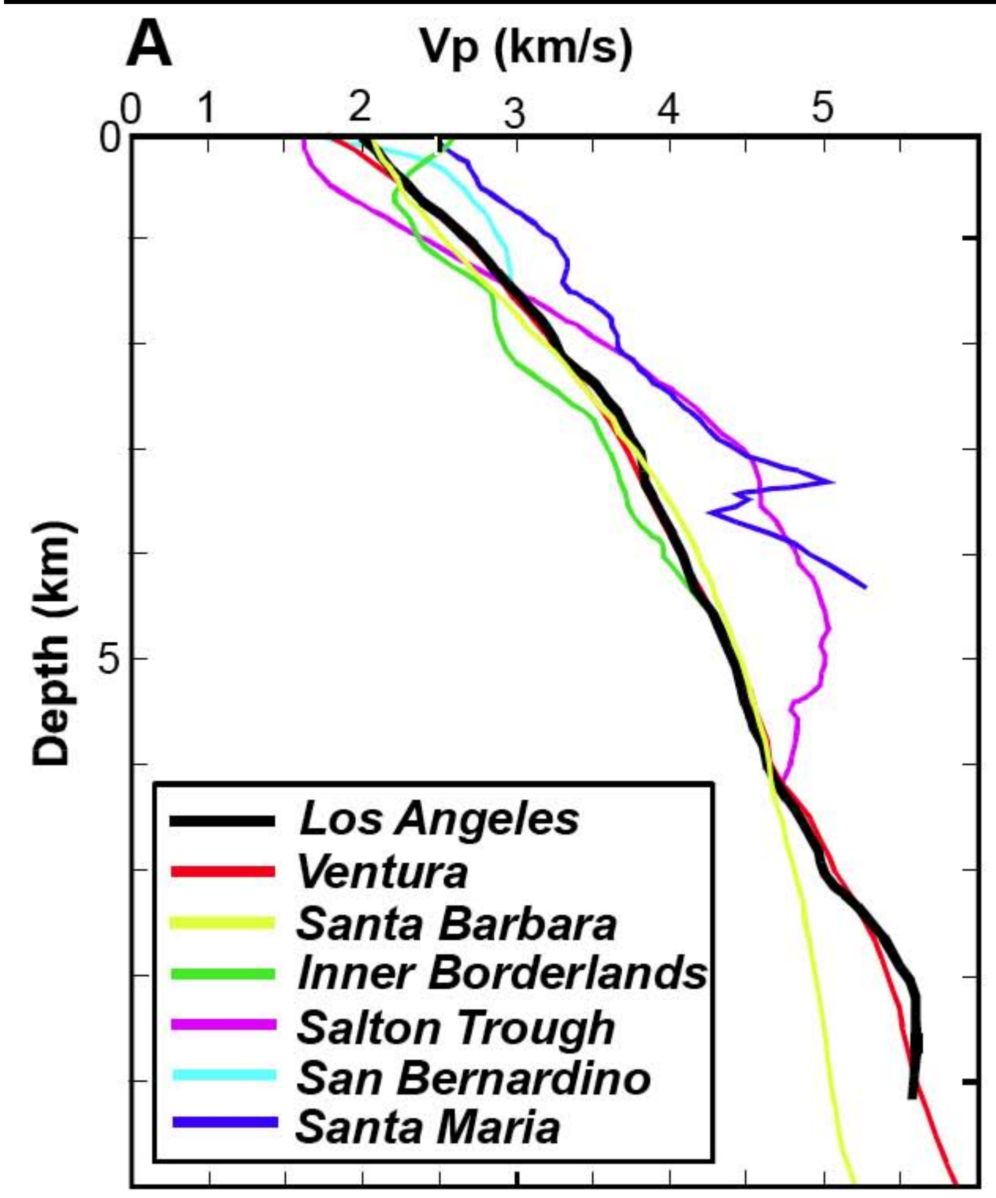
Shaw et al., (2013)

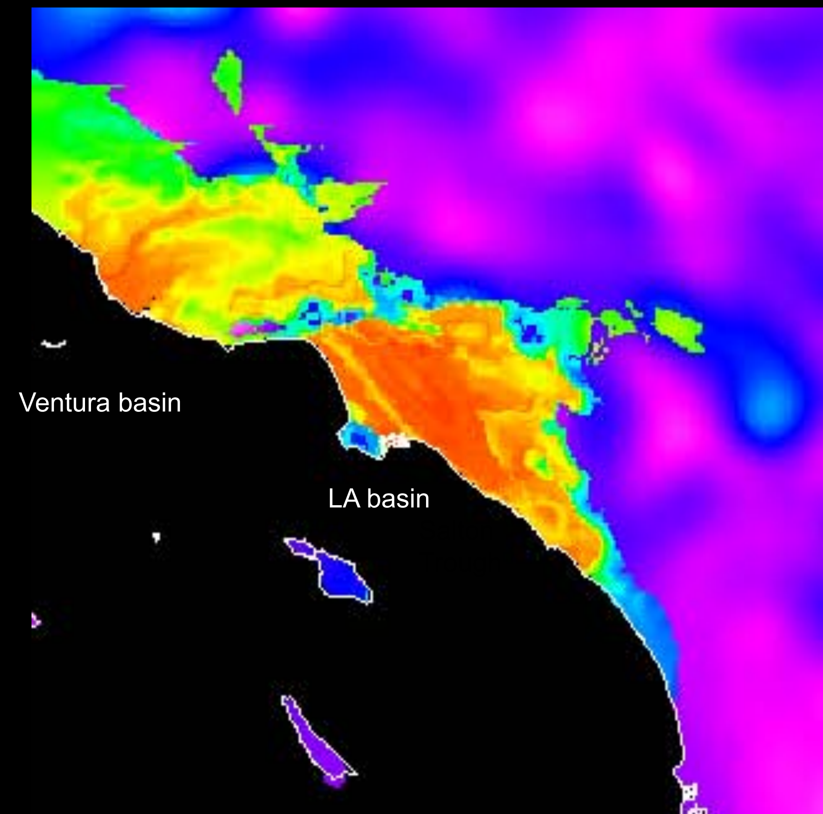
USR in SONGS study area



Shaw et al., (2013)

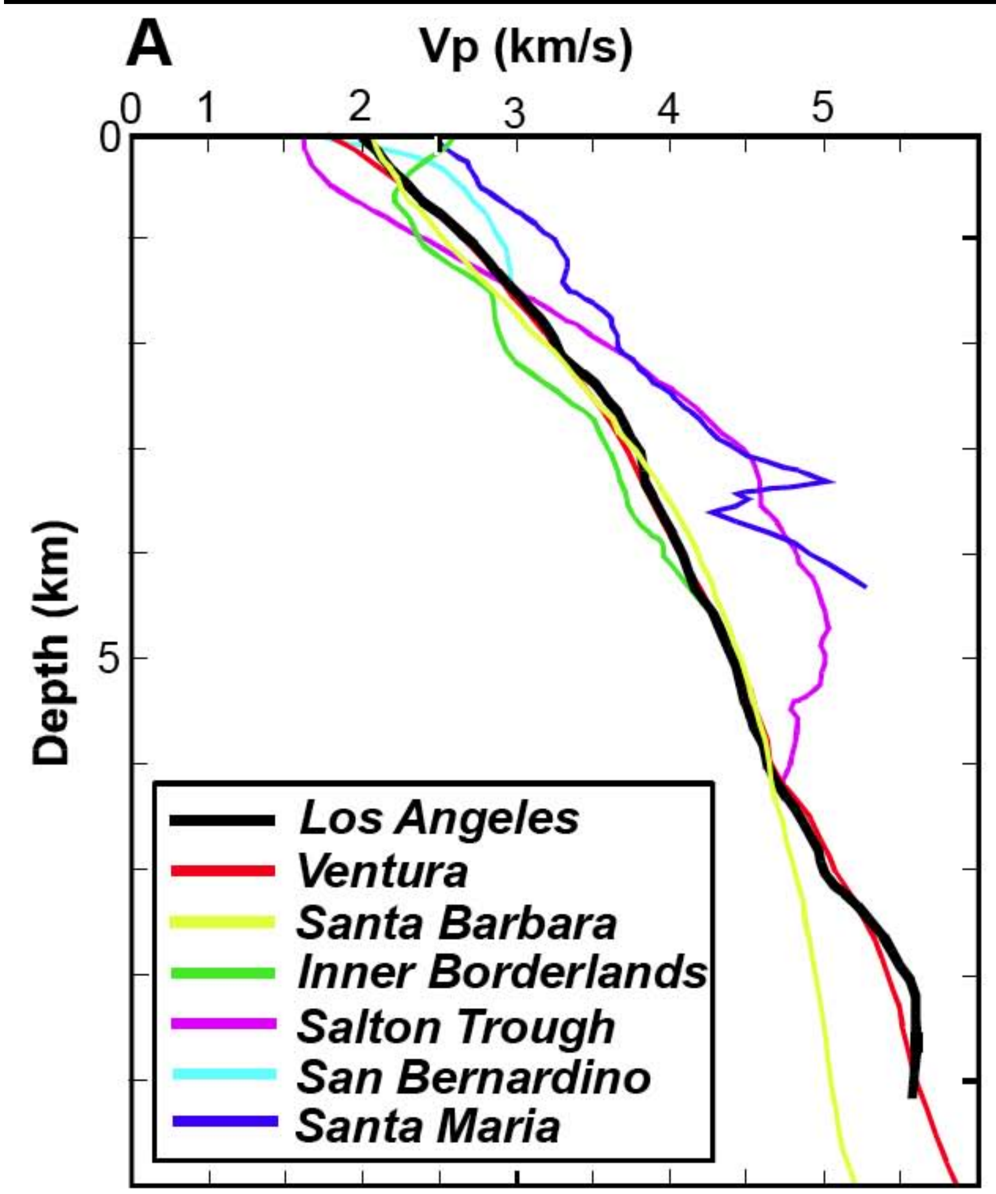
Basin velocity profiles

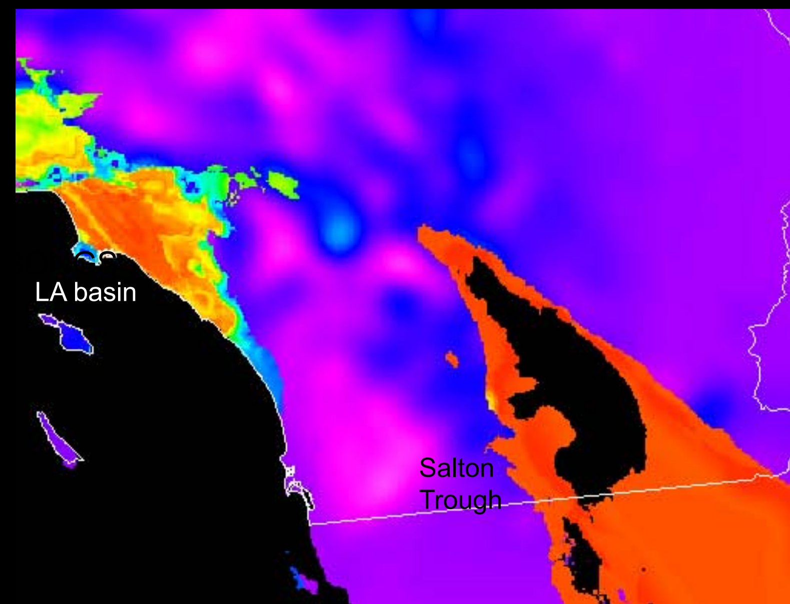




Shaw et al., (2013)

Basin velocity profiles

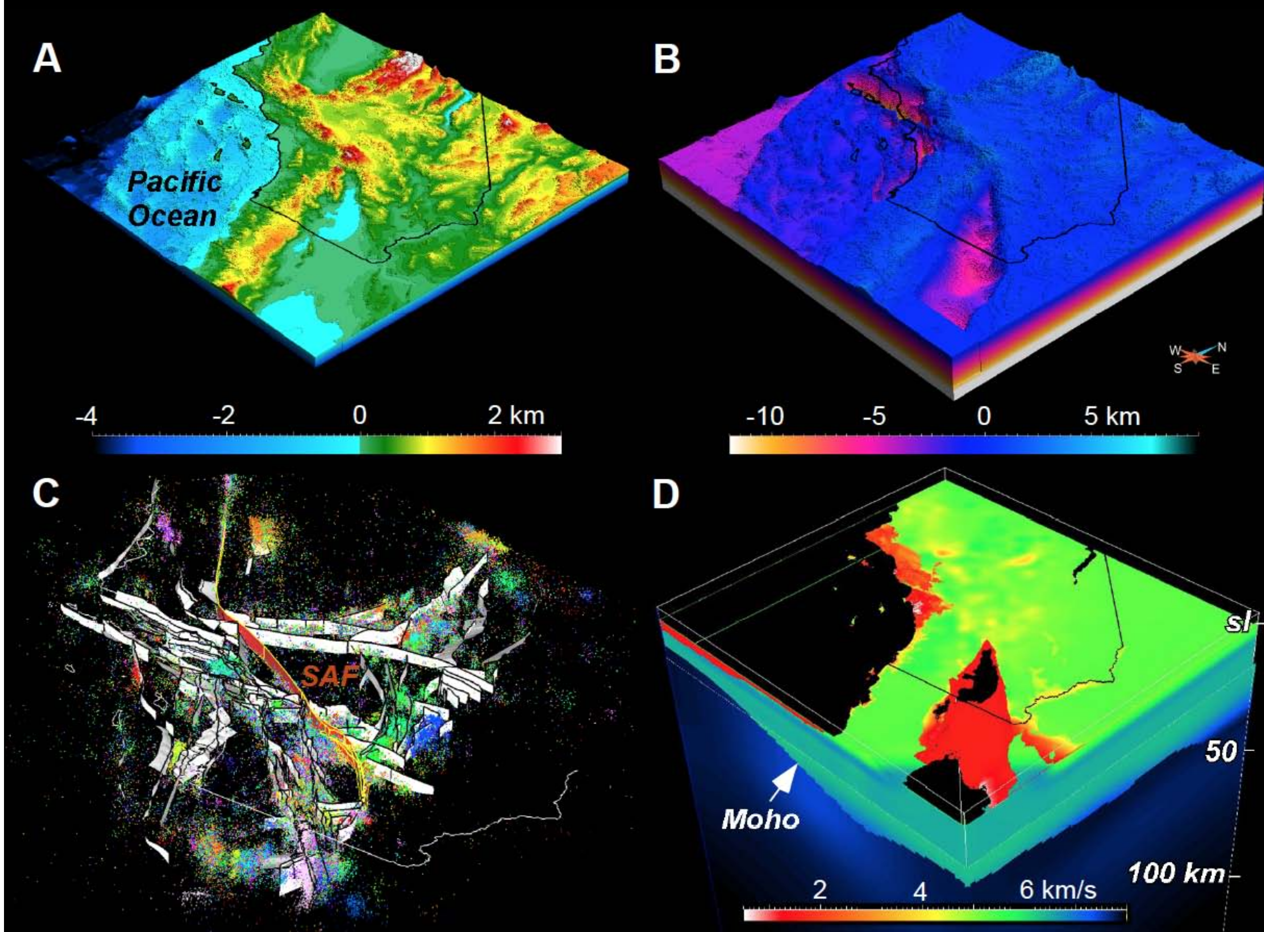




Salton Trough
basin

Shaw et al., (2013)

SCEC Unified Structural Representation (USR) Workflow



1) **Definition of geological and geophysical horizons**

2) **Incorpration of fault locations and displacements**

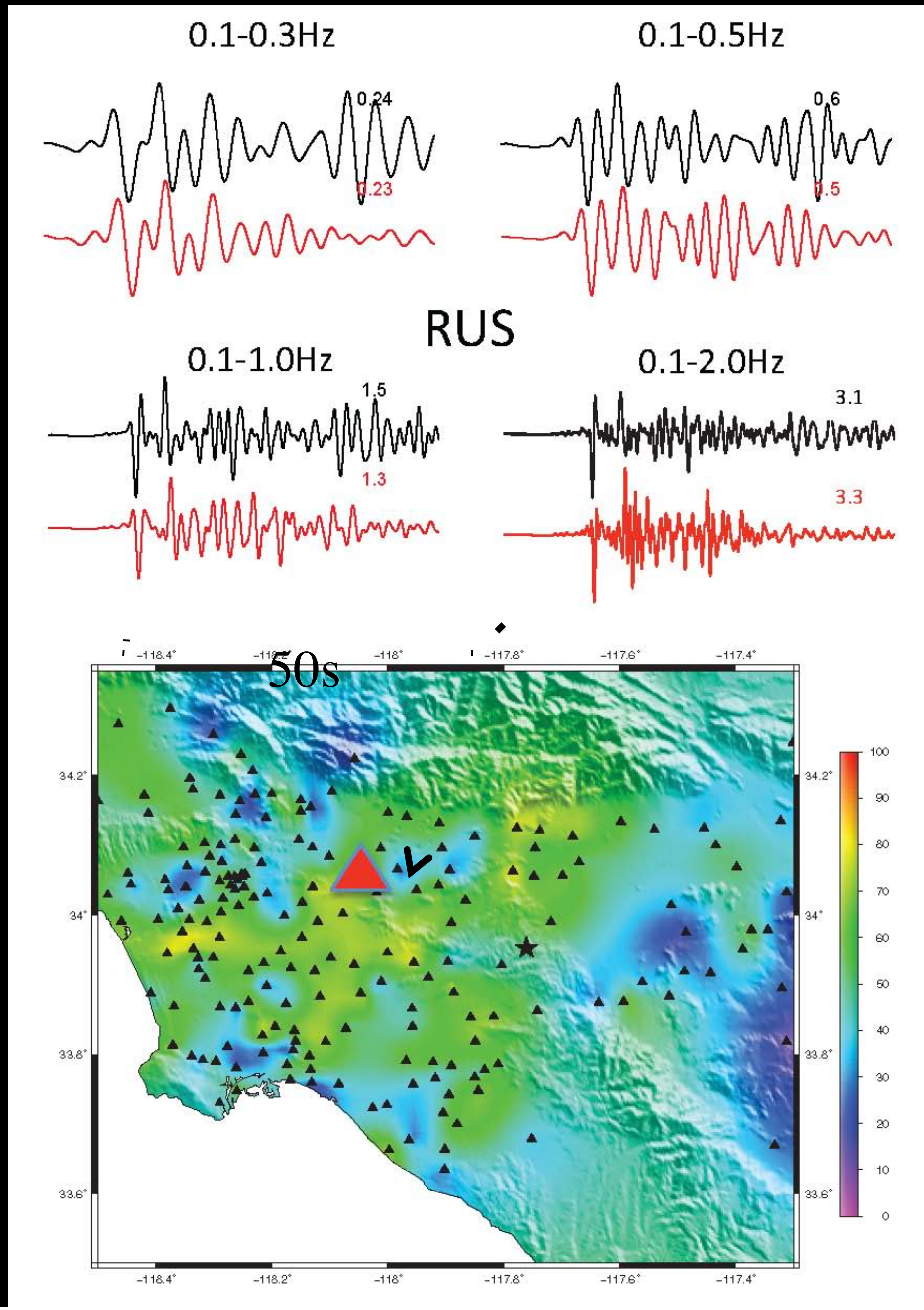
3) **Parameterization of sediment velocities**

4) **Embed basins in crust and upper mantle V models**

5) **Iteration of velocity models using 3D waveform tomography**

6) **Evaluating model performance & applications**

Evaluating the Community Models



Comparison of recorded data (black traces) and synthetics (red traces) for station RUS

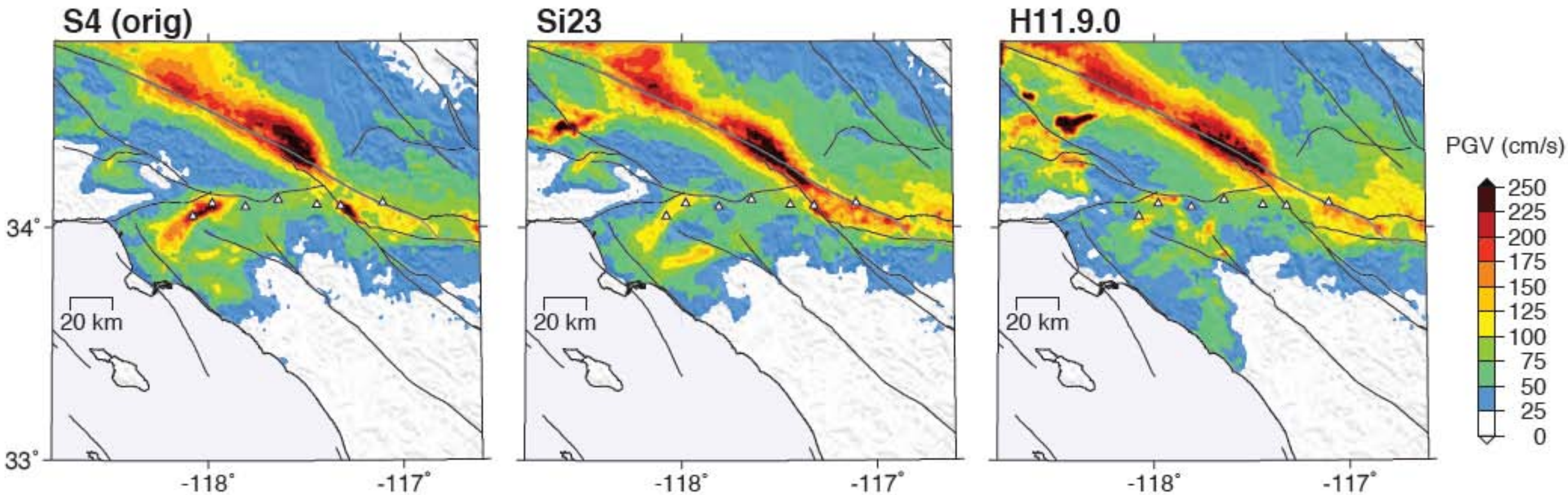
Average goodness-of-fit (perfect fit = 100) at 0.1-0.5 Hz for synthetics relative to data.

Olsen et al.

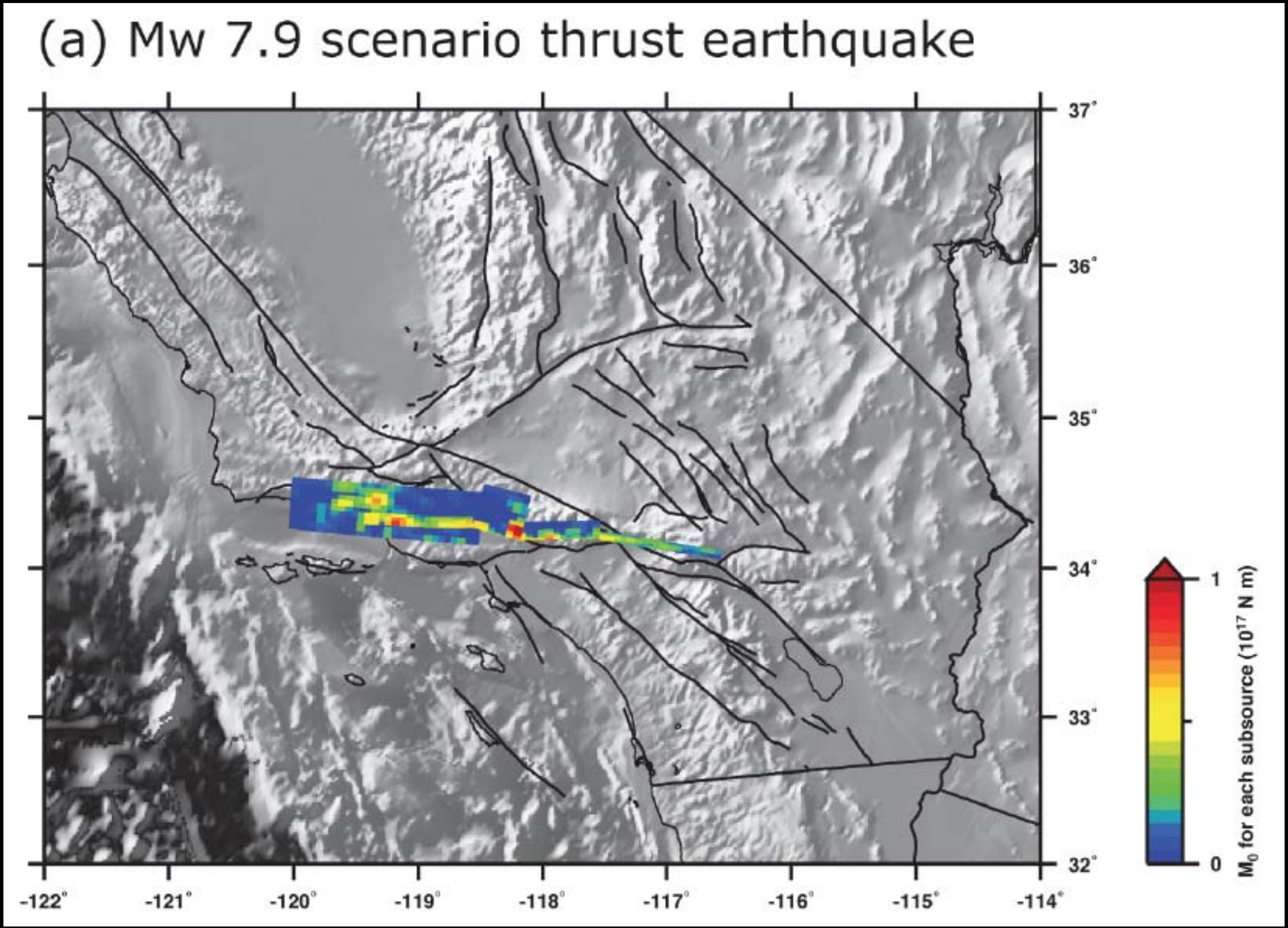
M7.8 ShakeOut Simulations in Alternative 3D Seismic Velocity Models

Rob Graves, USGS

- Panels below show peak ground velocity simulated for the three alternative CVMs. The plot at left (CVM-S4) is the original ShakeOut result from Graves et al (2008). The middle panel uses the CVM-Si23 update to CVM-S4 and the right panel is from CVM-H11.9.0.
- Along the fault, the general pattern is similar for all three models and is dominated by rupture directivity toward the Northwest.
- Other features are present in some models but not all. For example, both CVM-S4 and CVM-Si23 show strong amplification in San Bernardino, whereas CVM-H11.9.0 shows only modest amplification. On the other hand, both CVM-Si23 and CVM-H11.9.0 show strong amplification in the area north of San Fernando (Santa Clarita-Fillmore basin), but this feature is not present in CVM-S4.
- The Los Angeles basin region shows very strong amplification for CVM-S4 with PGV exceeding 50 cm/s throughout most of the basin, and reaching nearly 200 cm/s in the Whitter-Narrows region connecting the San Gabriel and LA basins. The level of amplification is noticeably reduced in CVM-Si23, and it is significantly reduced in CVM-H11.9.0.

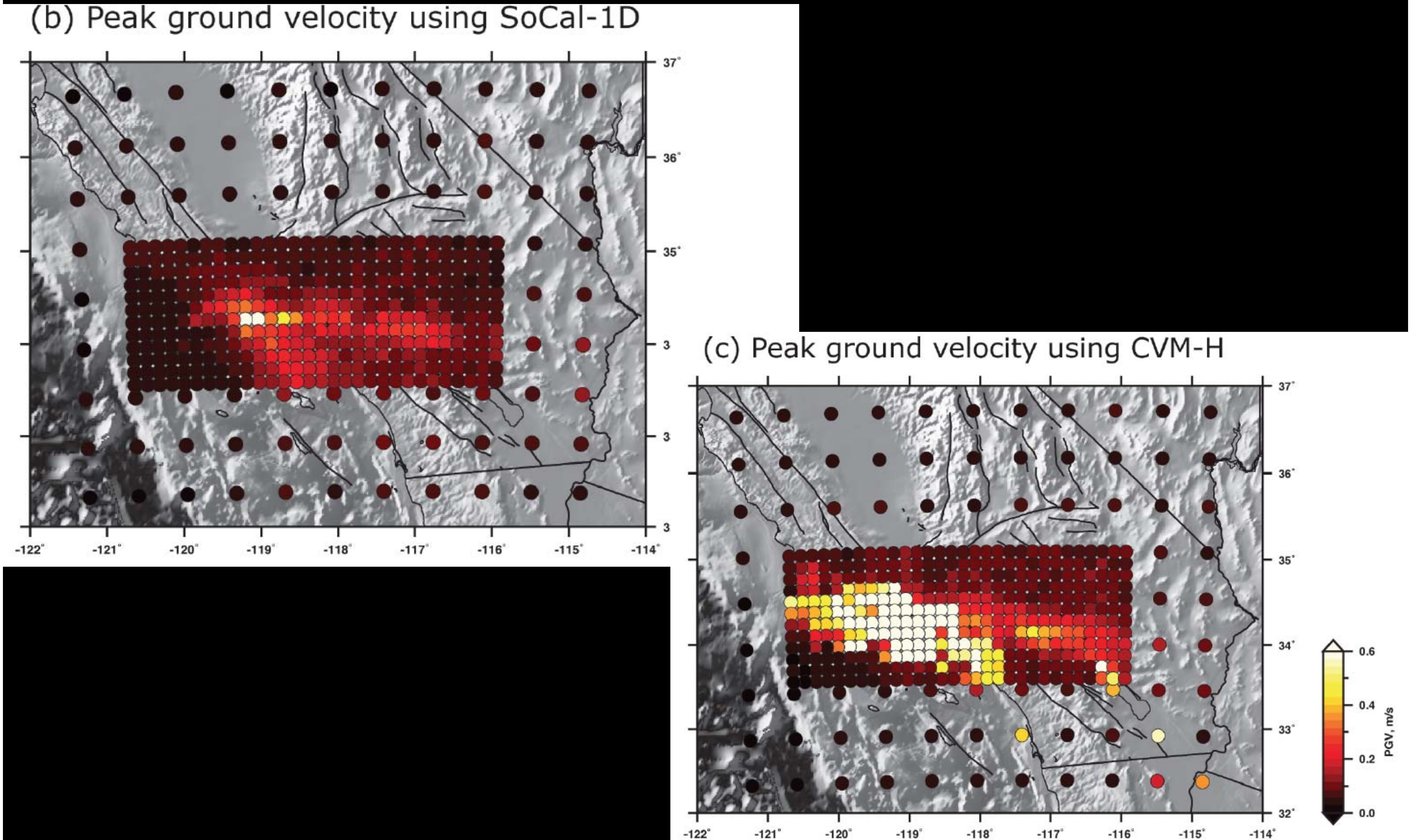


Strong ground motion forecasting

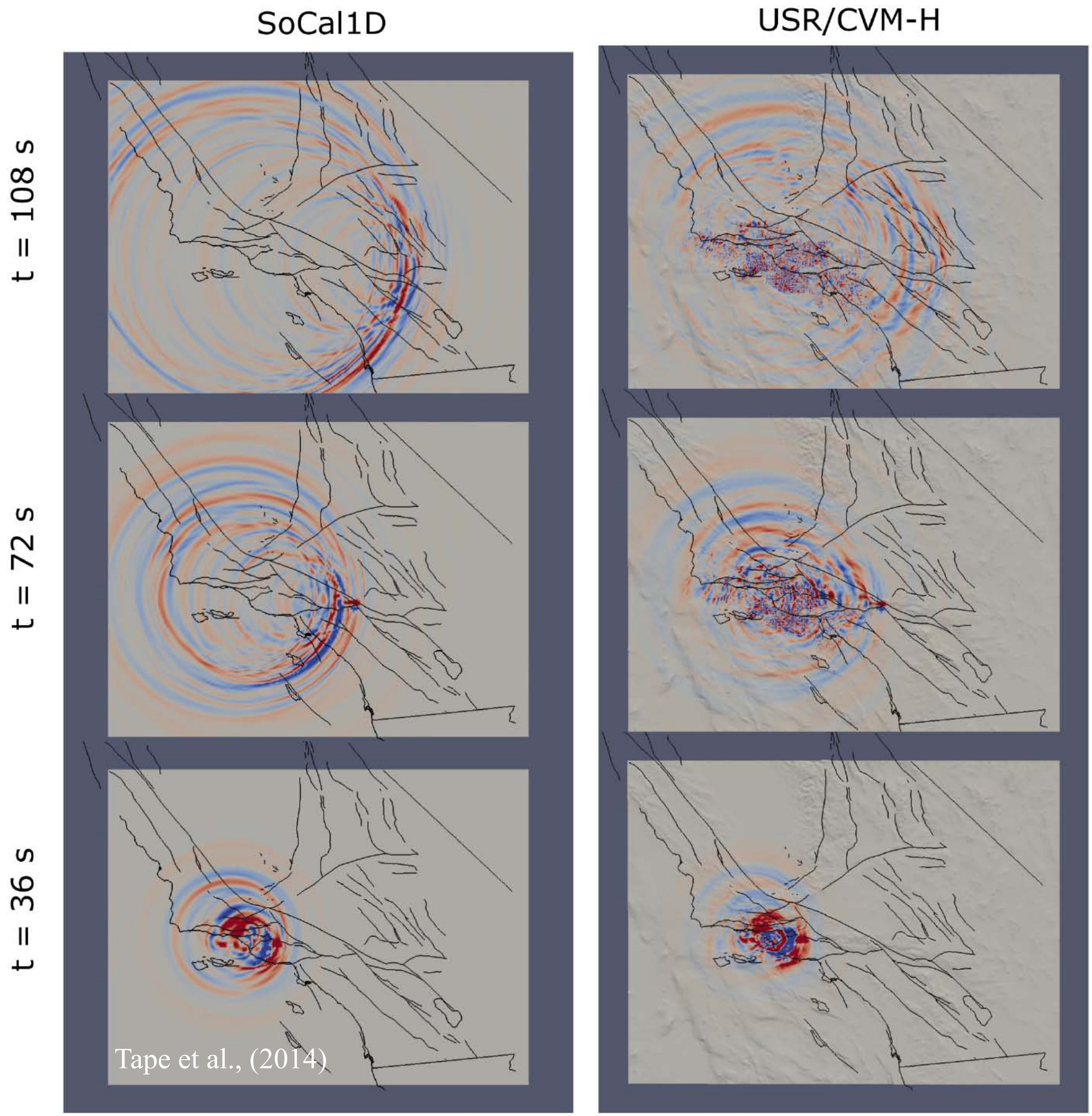


Tape et al., (2014)

Strong ground motion forecasting



Tape et al., (2014)


SoCal1D
USR/CVM-H
t = 108 s
t = 72 s
t = 36 s
Tape et al., (2014)

Developing Unified Structural Representations is a collaborative effort

John H. Shaw[1], Andreas Plesch[1], Carl Tape[1,2], M. Peter Suess[3], Tom Jordan[4], Geoffrey Ely[4], Egill Hauksson[5], Jeroen Tromp[6], Toshiro Tanimoto[7], Robert Graves[8], Kim Olsen[9], Craig Nicholson[7], Phil Maechling[4], Carlos Rivero[10], Peter Lovely[11], Charles M. Brankman[12], and Jason Munster[13]

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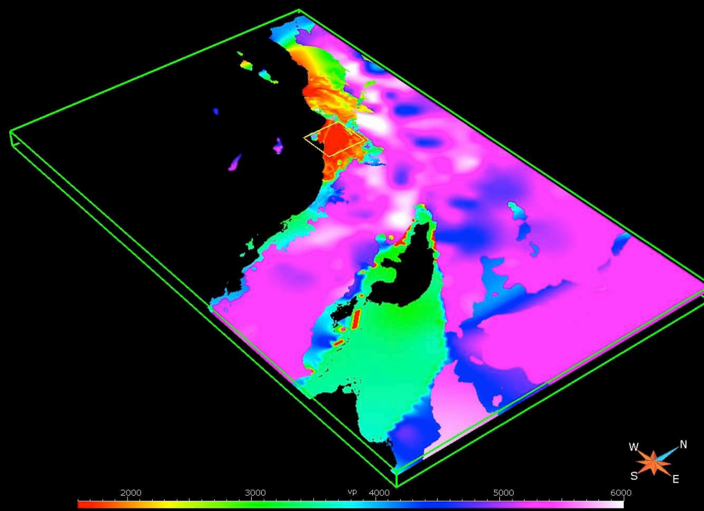
[2]University of Alaska Fairbanks, Geophysical Institute, 903 Koyukuk Drive, Fairbanks, AK, USA, 99775-7320
[3]Department of Geosciences, Tübingen University, Hölderlinstr. 12, 72074 Tübingen, Germany
[4]Southern California Earthquake Center, University of Southern California, Los Angeles, CA, USA, 90089-0742
[5]Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA , 91125
[6]Department of Geosciences, Princeton University, Guyot Hall, Princeton, NJ, USA, 08544
[7]Department of Earth Science, 1006 Webb Hall, University of California Santa Barbara, CA, USA, 93106-9630
[8]U.S. Geological Survey, 525 South Wilson Avenue, Pasadena, CA, USA, 91106
[9]Dept. Geological Sciences, MC-1020, 5500 Campanile Dr., San Diego State University, San Diego, CA, USA, 92182-1020
[10]Chevron North America E&P, Gulf of Mexico Regional Team, Houston, TX, USA, 77002
[11]Chevron ETC – ESD, 1500 Louisiana, 28077, Houston, TX, USA, 77002
[12]IHRDC, 535 Boylston Street, Boston, MA, USA, 02116
[13]School of Engineering and Applied Sciences, Harvard University, 29 Oxford St., Cambridge, MA, USA, 02138



SCEC ERI Workshop

Monday 3:30-6:30pm: **3D Structural Velocity Modeling/USR Framework**

Goal: This afternoon's exercises are designed to familiarize you with the components of 3D structural velocity models, including basin structures, faults, and velocity parameterizations. We will accomplish this using the SCEC Unified Structural Representation (USR) for southern California and two tools developed to access and use this model: SCEC VDO, and interactive 3D visualization tool, and UCVM, which allows you to extract velocity values from these models.

Schedule

3:30 pm: Laptop setup, virtual box instructions

3:45pm: SCEC-VDO: Structural components
Basics: navigation, loading plugins and datasets
Visualizing faults: SCEC CFM
Visualizing geologic surfaces: Basement and Moho surfaces
Exercise: Examining faults that affect the Basement surface

SCEC ERI Workshop

Monday 3:30-6:30pm: **3D Structural Velocity Modeling/USR Framework**

4:15pm: SCEC-VDO: Exploring velocity models
Examining velocity cross-sections
Examining velocity maps
Exercise: Comparing velocity structures and geologic surfaces

4:45 – 5pm: BREAK

5pm: UCVM
Introduction to the UCVM framework
Plotting cross sections and maps
Exercise: Comparing alternative velocity parameterizations
Extracting 1-D velocity profiles
Exercise Evaluating basin velocity structures

6:30 Conclude

Challenges in USR development

- Consistent representations of other seismic parameters (e.g., attenuation)

- Frequency dependence of velocity and other seismic properties

- Representing small scale velocity heterogeneity (stochastic approaches)

- Incorporating new local constraints on velocity structure in 3D waveform tomographic inversions

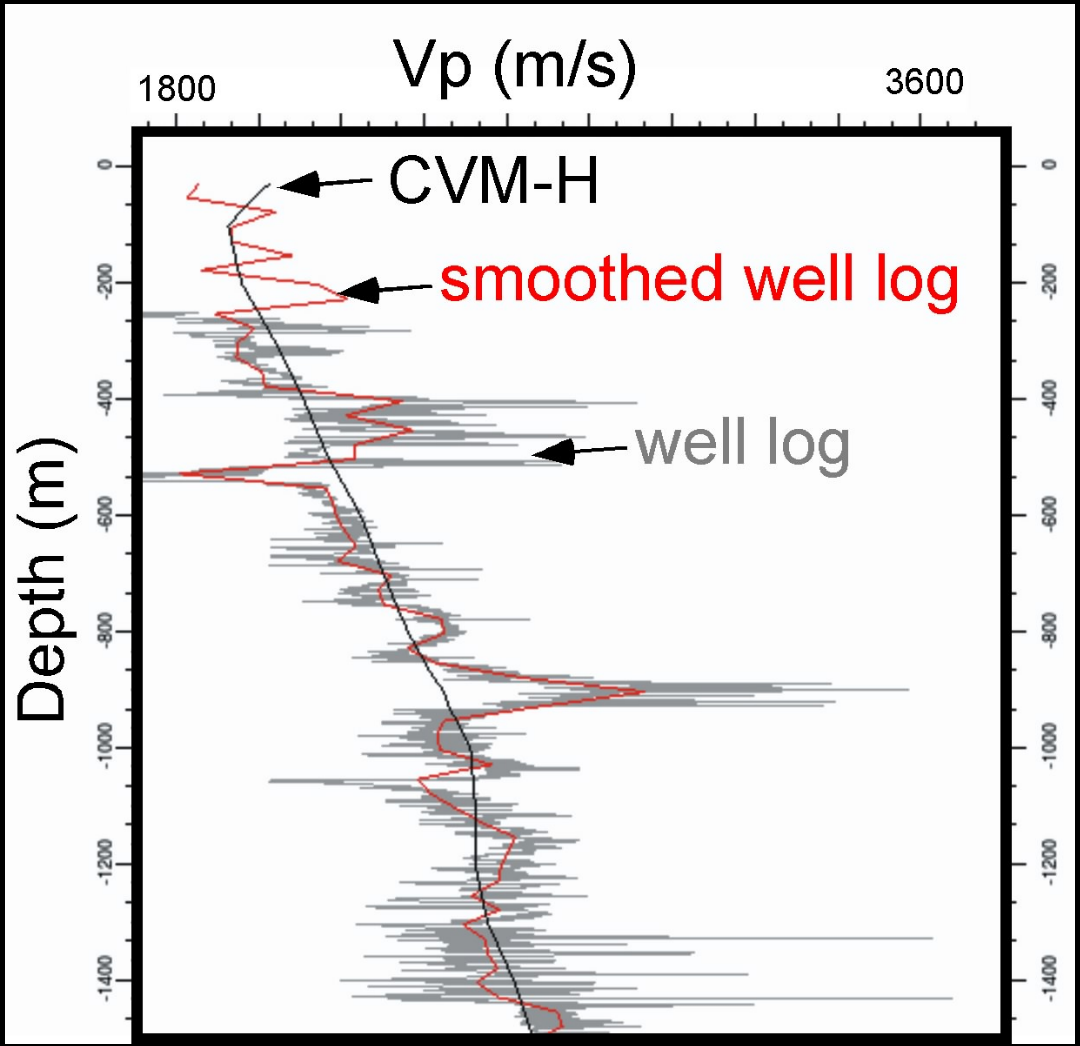
- Maintaining and distributing a growing inventory of models and model iterations

High-frequency velocity structure

Plesch, Shaw, Jordan, Song (2014)

The CVM-H was parameterized using a smoothed version of sonic log data.

Comparison of the CVM-H 11.9 with the original log data reveals the nature of high-frequency velocity structure that is not captured by the model, but can be represented statistically.



Stochastic Descriptions of Basin Velocity Structure from Analyses of Sonic Logs and the SCEC Community Velocity Model (CVM-H)

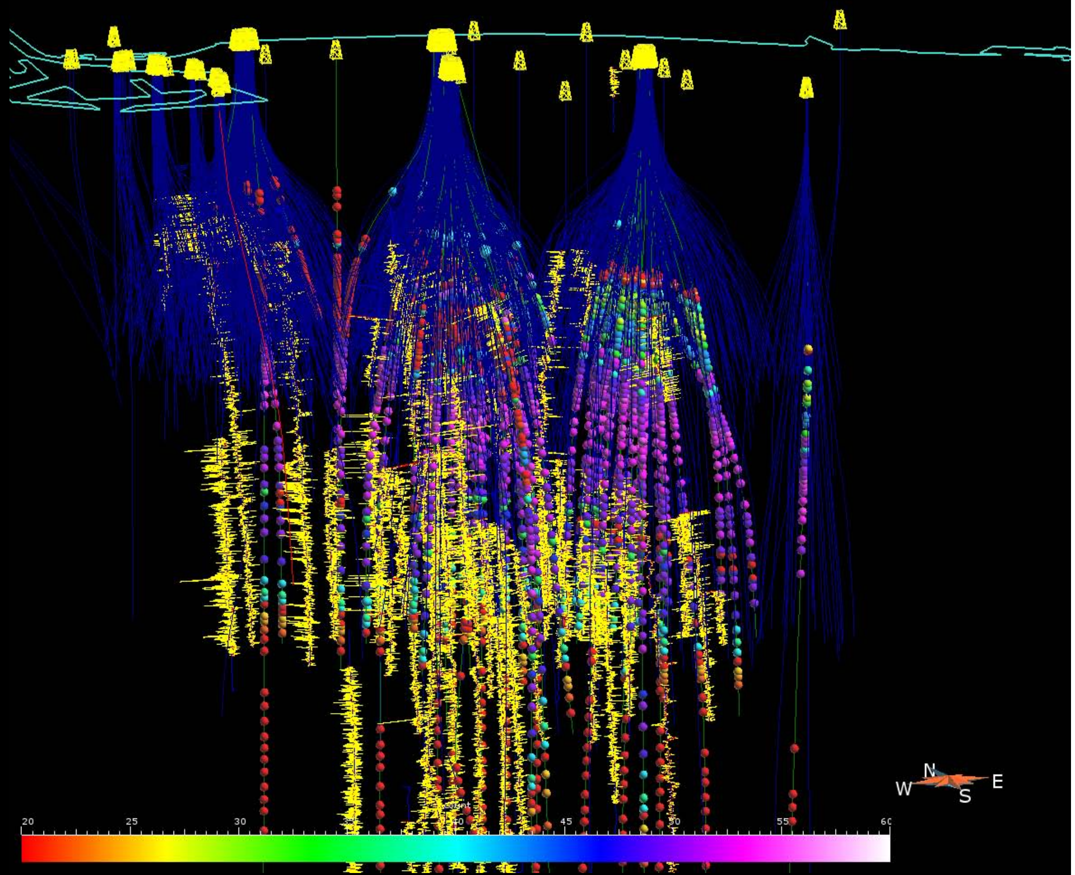
A. Plesch, J. H. Shaw , T. Jordan, X. Song

Results:

- LA basin wide analysis shows a 6.5% overall variability in Vp relative to CVM-H for the small (7m) length scale, and that the variability distribution is not Gaussian.

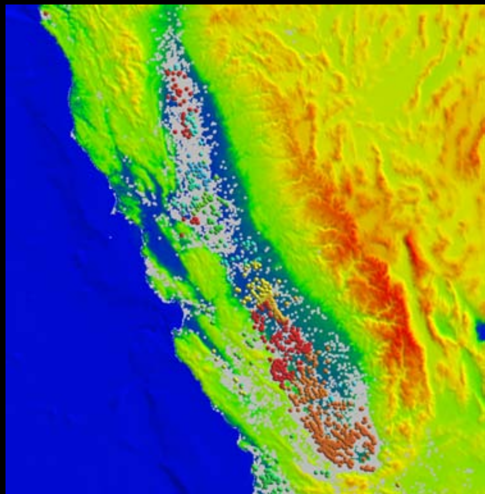
- variogram analyses reveals a (maximum) vertical correlation distance for Vp of 80-100m

- analyses of clustered wells in Wilmington field data (right) shows horizontal correlation distance for Vp of ≈ 1000m.



Wilmington field: 70 well paths on 7km x 2.5km with data, >1.1 million samples of interval travel times by logging tools (converted to Vp); logs in yellow and tops as spheres

Faulted basement surface



Faults can act as both basin boundaries and internal structures that offset horizons