Incorporating Complex Geology in Basin Models: Example from a Forearc Basin; San Joaquin Valley, California*

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Abstract

The San Joaquin Basin lies west of the Sierra Nevada Mountains and east of the San Andreas Fault. Tens of kilometers of Mesozoic and Cenozoic sediments, including deep-water organic-rich source rocks, deposited in a forearc setting, comprise the basin and have contributed to a petroleum system that generates more than 70 percent of California's daily oil production and includes three of the 10 largest oilfields in the United States. Based on a comprehensive 3D petroleum systems model of the San Joaquin basin, published by the USGS in 2008, we further refine the modeling to account for the unique depositional and tectonic history of the basin. Here, we compare various basal heat flow scenarios to model hydrocarbon generation and calibrate the results to available temperature and vitrinite reflectance (Vr) data. We investigate two types of crustal models: a McKenzie-type rift model, and a no-rift static crustal thickness model. Crustal stretching models calculate basal heat flow resulting from stretching/thinning of mantle and crust during initial (syn-rift) and thermal (post-rift) subsidence. This method uses rock matrix radiogenic heat production values. It does not account for transient effects resulting from burial and uplift of the basin fill. The static no-rift model, alternatively, calculates the basal heat flow based on a stable or non-thinning crust and mantle over time. This method uses estimated Uranium (U), Thorium (Th), and Potassium (K) concentrations within the rock material to then calculate the rock matrix heat production. Unlike the rift model, it accounts for the transient effects resulting from burial and uplift of the basin fill, which can have a considerable additional effect on the basal heat flow. Given the low probability of crustal stretching as the starting point for basal heat flow in the San Joaquin Basin and considering the forearc nature of the basin as well as the strong concentration of U, K, and Th in the Sierran granites, we focused on and refined the no-rift models. We manually account for the transitional nature of the San Joaquin basement from hot Sierran granite on the east to cool Franciscan oceanic rocks on the west. Radiogenic heat production from solely continental crust results in models that are too warm and cannot be calibrated to well temperature and Vr data. Solely oceanic models are too cool to match well data. 'Combined crust' incorporates a seismically derived suture zone that allows for a transition from oceanic to granitic basement, while the 'intermediate crust' mixes oceanic and continental radiogenic heat production. These models generate a good match to well data to the east and westward through the transition zone. Additionally, we are able to calibrate to wells off of the Belridge and Lost Hills structures. On structure wells, however, cannot be calibrated with a crustal conductive heat flow scenario and would require (local) elevated heat flows on the order of 20 mW/m^2. This is not in agreement with the generally cooler underlying oceanic crust and suggests that there might be a different and/or

additional source of heat flow. Most likely, basin-scale hydrothermal groundwater flow, both along faults and up-structure, could account for elevated Vr and temperature. Convective heat flow would be an additional overprint or enhancement to conductive basal heat flow.

Selected References

Burton, C.A., and K. Belitz, 2012, Groundwater Quality in the Kern County Subbasin, California: USGS Fact Sheet 2011-3150, Web Accessed November 19, 2016, http://pubs.usgs.gov/fs/2011/3150/

McKenzie, D., 1978, Some Remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25-32.

San Joaquin Valley Geology, 2016, Introduction to the Geology of the San Joaquin Valley: Web Accessed November 19, 2016, http://www.sjvgeology.org/geology/

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Basin Modeling Basics

- Why do we create basin models?
  - If we can generate hydrocarbons in a model that matches the known HC generation patterns and quality AND
  - we can migrate hydrocarbons in the model to where we already know they are
  - Then we can predict where we might find more HC

What do we need to know for a basin model to work?

- Hydrocarbon Generation -
  - What was buried?
    - Lithology, TOC
  - How deep was it buried?
    - Geometry, paleo-geometry
  - For how long?
    - Maturity
  - Was it hot enough?
    - Thermal history (subsidence, initial heat, RHP, conductivity)
- Hydrocarbon Migration
    - Structural (buoyancy) – Structural highs? Synclines?
    - Lithologic controls – Permeability, porosity, fractures?

What was buried?

Upper Antelope

TYPE	SS_percent
Stevens Sand Lobe	80
Shelf to Inner Slope	40
Basinal - Deep Marine	0
Outer Slope	20

Mid Antelope

TYPE	SS_percent
Stevens Sand Lobe	80
Shelf to Inner Slope	40
Basinal - Deep Marine	0
Outer Slope	10
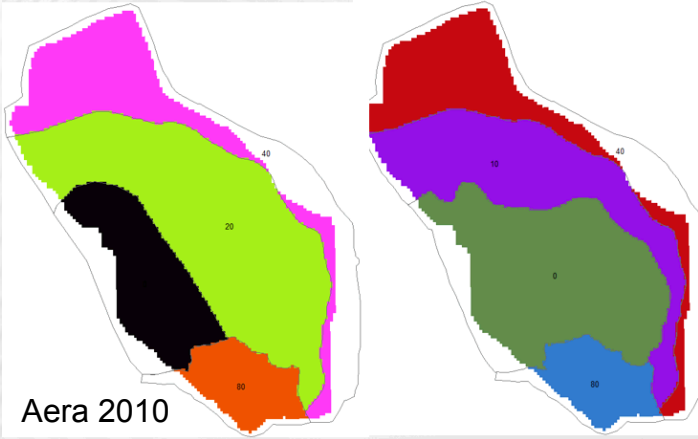
Monterey TOC

TYPE	TOC_Percen
Basinal - Deep Marine	6
Shelf to Inner Slope	2
Basinal - Deep Marine	6
Outer Slope	4

Aera 2010

Aera 2010

How deep did it get?

Lampe, 2014

AERA
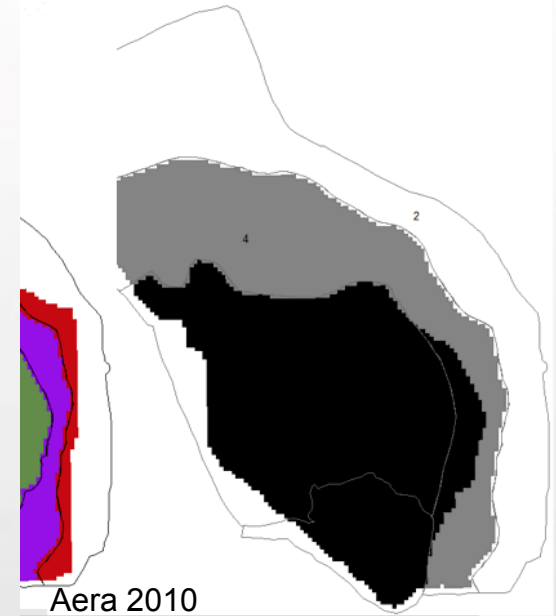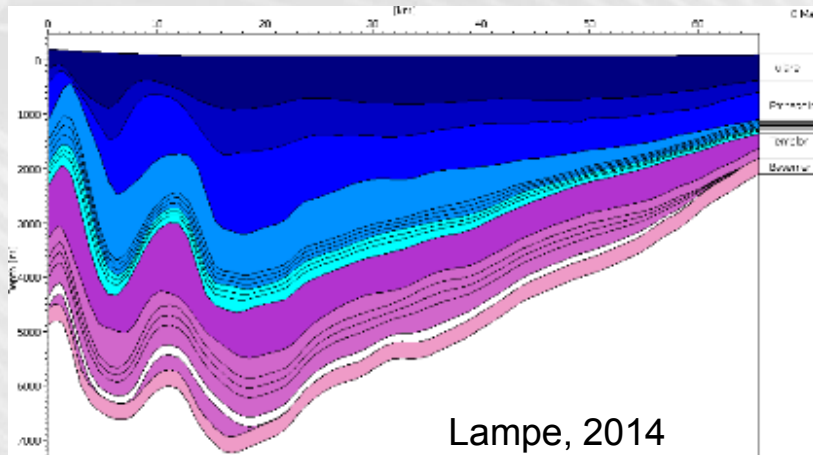
How long was it buried?

Lampe, 2014
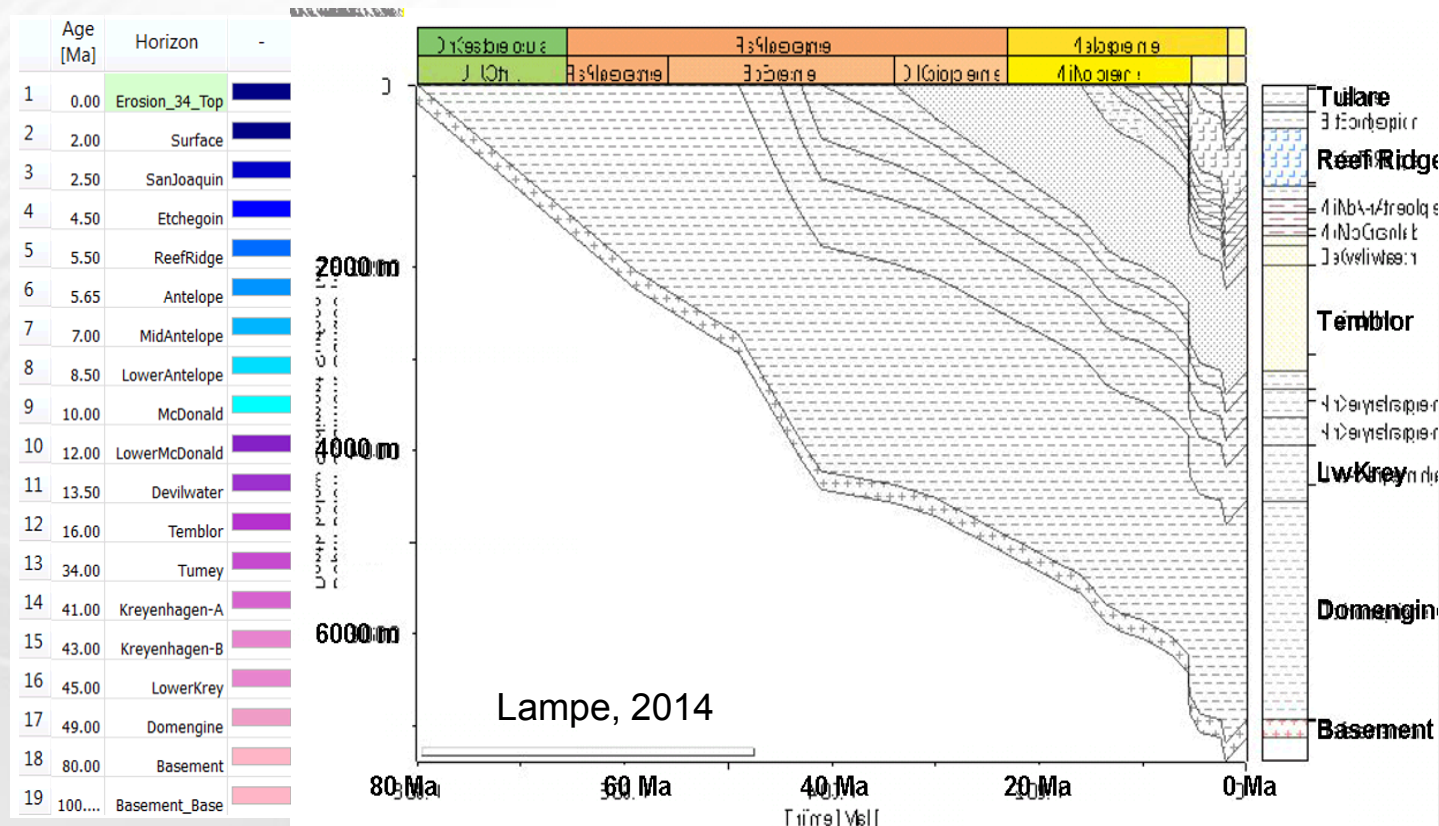
How hot did it get?

Here is the crux of the issue.
There are numerous ways to provide a starting point for hydrocarbon generation. You need to assign the basin a starting temperature profile. From this point, additional heat can be added/subtracted due to rock properties, subsidence, etc. These values are sometimes known but most times are allowed to vary to generate a match to the known data (in this case, thermal maturity measured from drilled wells)

Typical Heat flow scenarios

- We discuss here two main starting points for setting the initial temperature profile. One is a "rifted" approach, which assumes that the crust below the basin your are trying to model was initially thinned from a normal thickness during an instantaneous rifting event.

- The other is a crustal layer model that has an initial crustal heat flow due to rock properties (radiogenic heat flow) but gains/loses heat over time due to burial and/or subsidence.

"Rift" model

Thermal Model

Temperature perturbation is a function of the amount of stretching, β, and is uniform along the profile.

Pre-Rift Geotherm = T=Tm(1-z/a), where z is the depth.

Post-Rift Geotherm =

    T=Tm*β(1-z/a) from the surface to the base of the crust, and

    T=Tm below the crust.
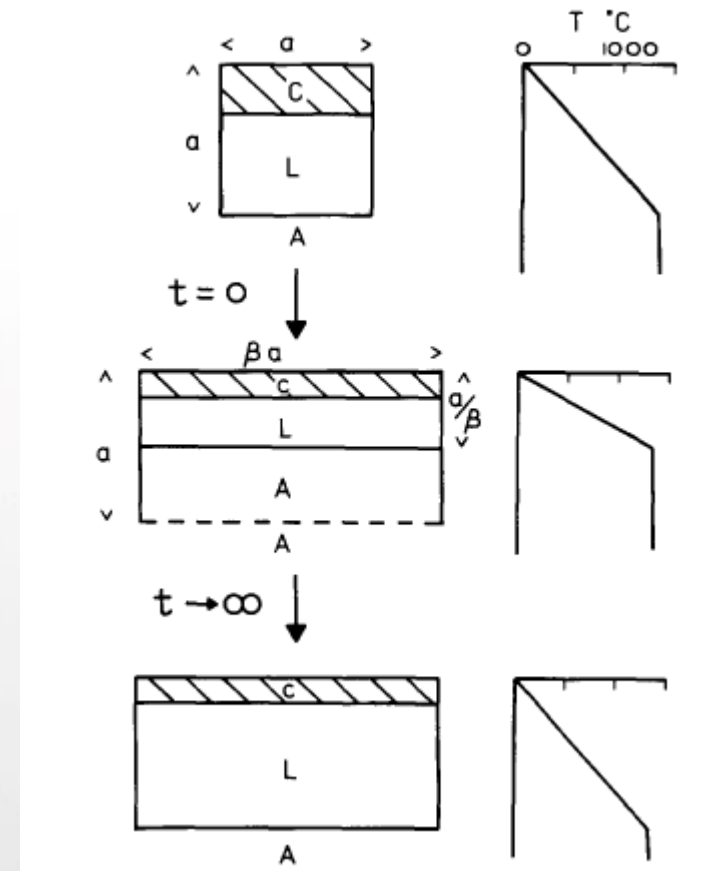
McKenzie, 1978

Implementation of Analytical McKenzie (1978) Model – Compressed post-rift geotherm is a function of beta.

Pre-Rift Temperature Profile
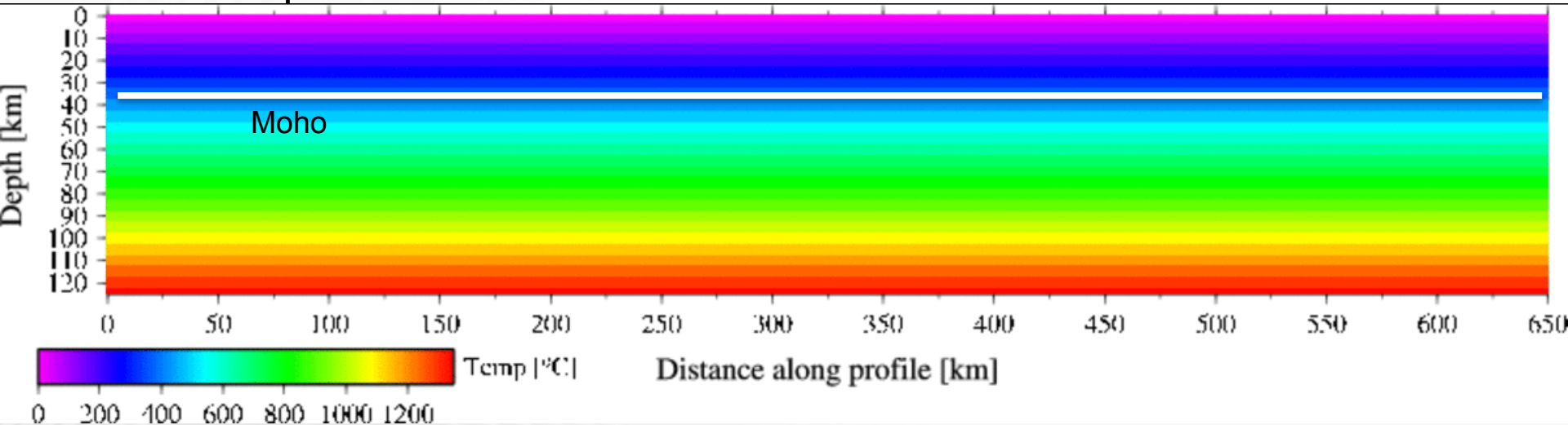
5 Million Years after rifting event
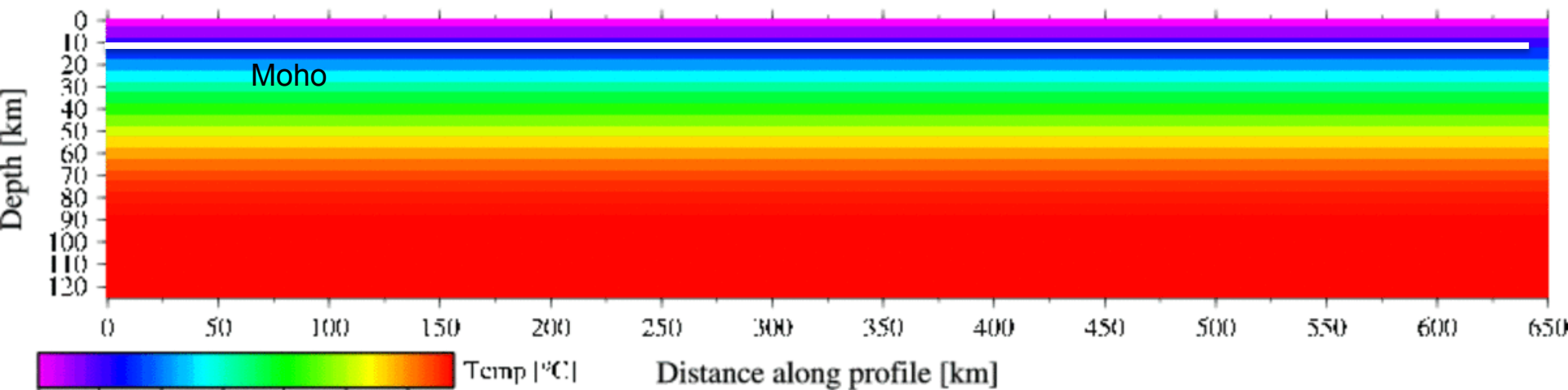
Crustal Layering Model

- Calculates the basal heat flow based on a "stable" (non-thinning) crust and mantle over time

- Incorporates the U, Th, and K content of the rock type

- Considers transient effects resulting from burial and uplift of the basin fill, e.g. strong subsidence causes a decline in both basal and surface heat flow, uplift would result in an increasing heat flow

- Does _not_ allow a spatial variation of radiogenic heat production.

Which one is appropriate?

Geologic Setting – San Joaquin Basin

(http://pubs.usgs.gov/fs/2011/3150/)

(http://www.sjvgeology.org/geology/)
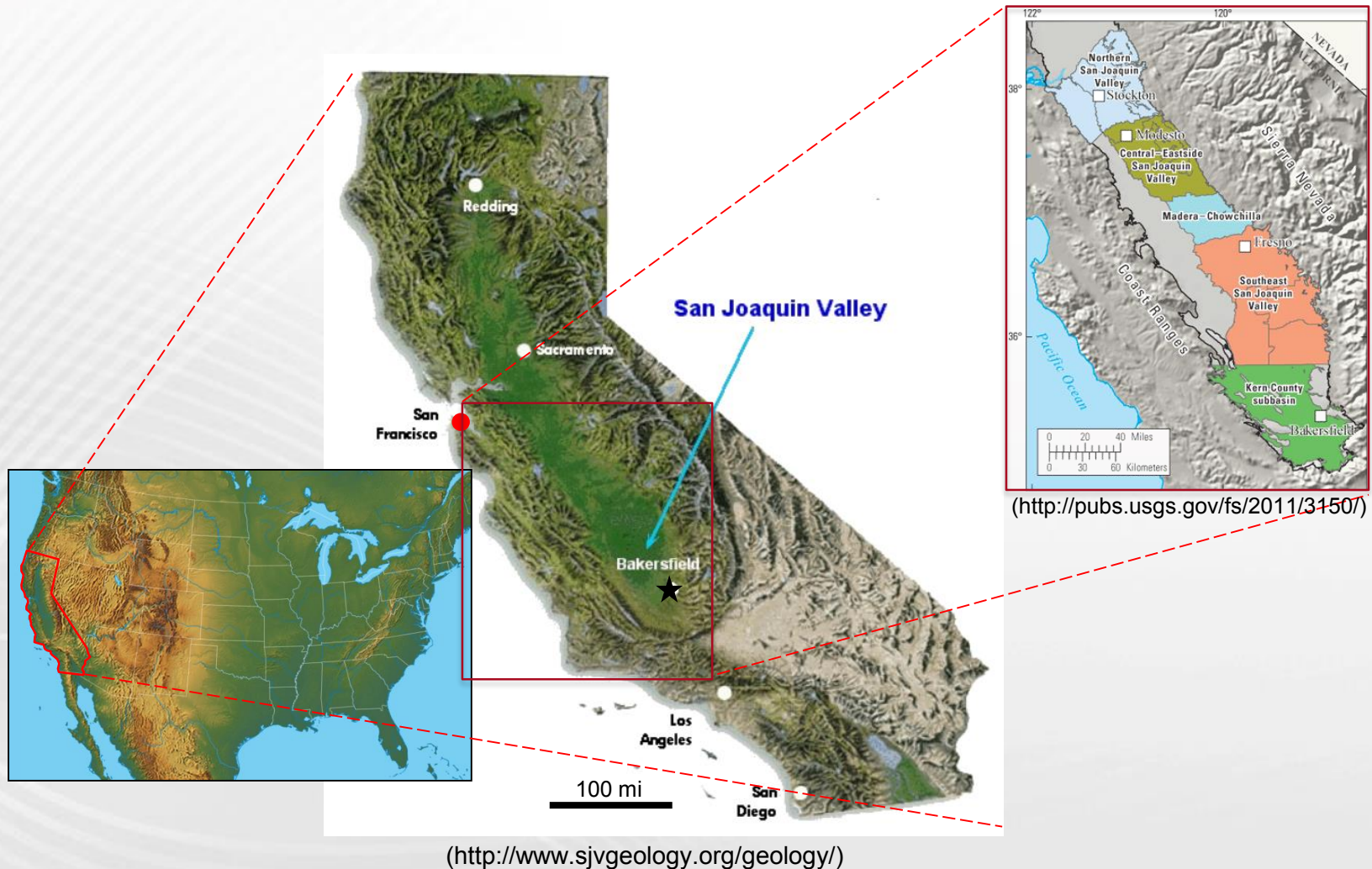
Structural Setting – San Joaquin Basin

http://www.sjvgeology.org/history/calif_relief.gif

SJ Basin is a **forearc basin** bound to the west by the Coast Ranges and to the east by the Sierra Nevada.

The basin formed during Mesozoic subduction and has since been modified by transpression associated with the San Andreas Fault

Interbedded marine and non-marine sources comprise SJB stratigraphy
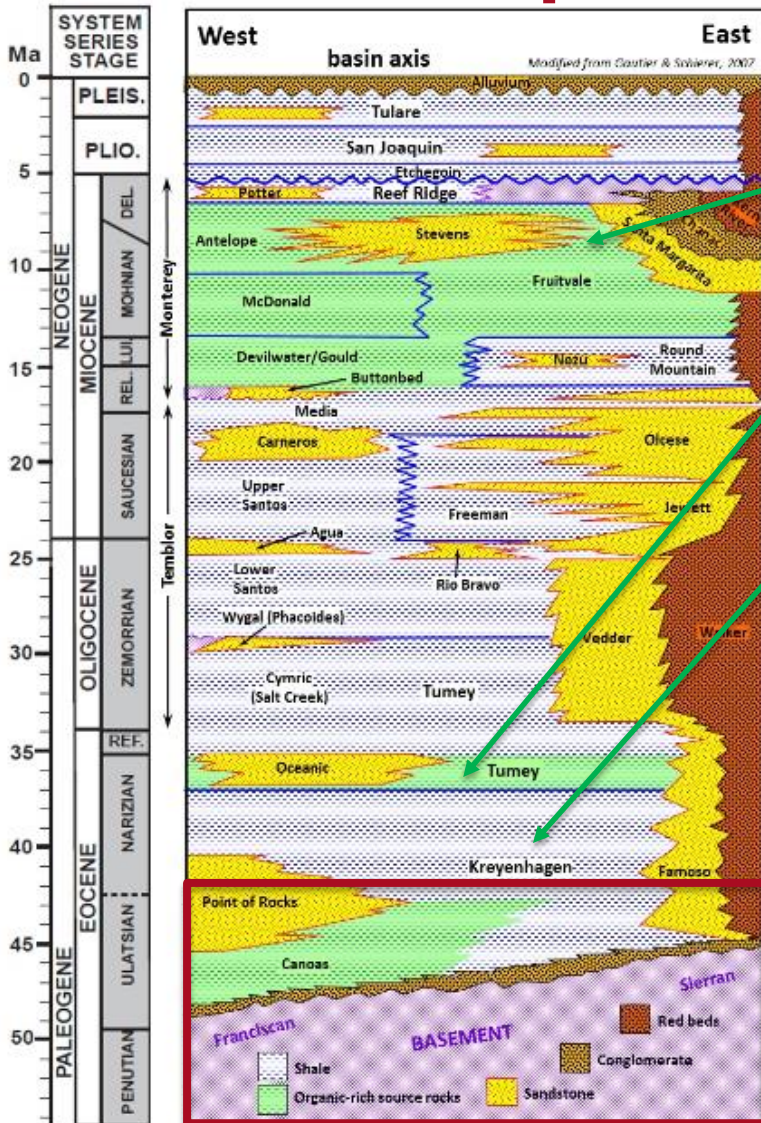
Source rocks	Interbedded sands
Monterey	Stevens, Potter
siliceous shales	turbidite sandstone
diatomite (chert)	
Tumey	Vedder Sandstone
shales	turbidite sandstone
basal sandstone	
Kreyenhagen	Point of Rocks
biosiliceous shale	turbidite sandstone
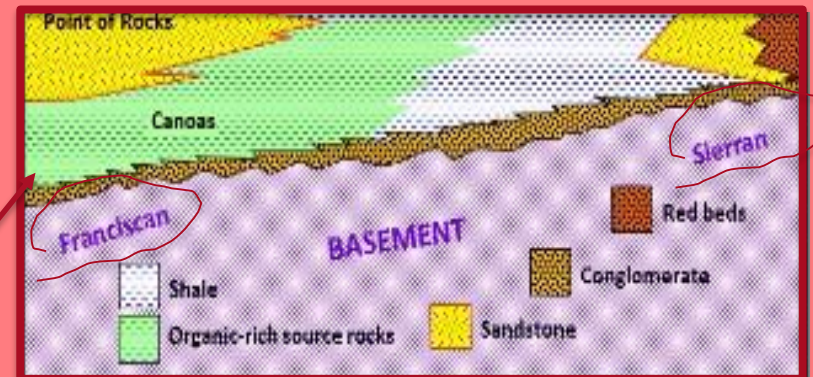
Basement accuracy is crucial for radiogenic heat production
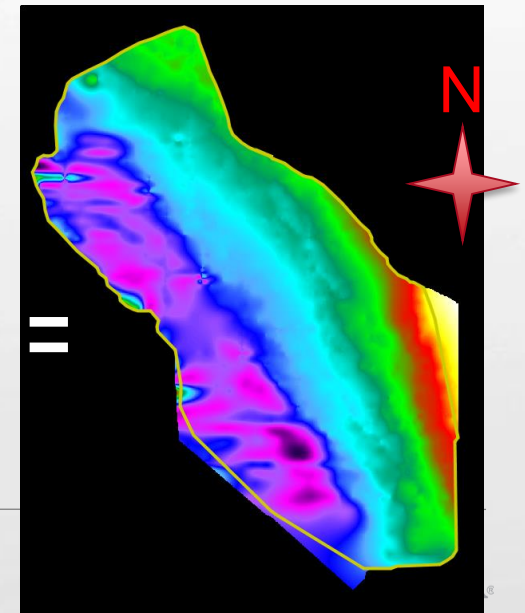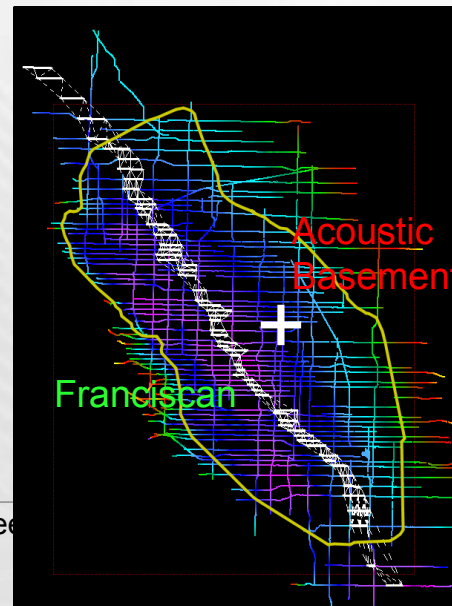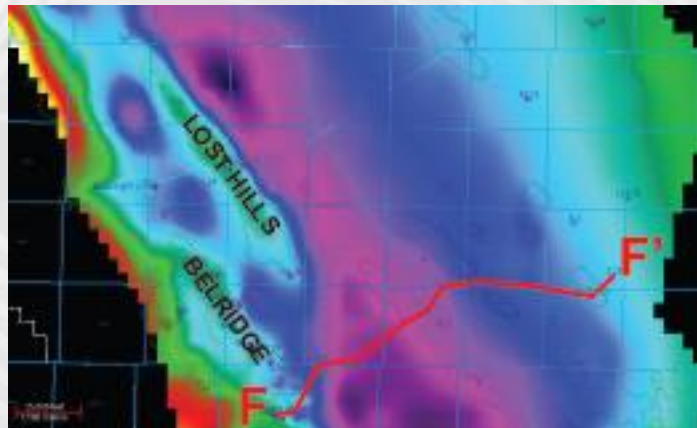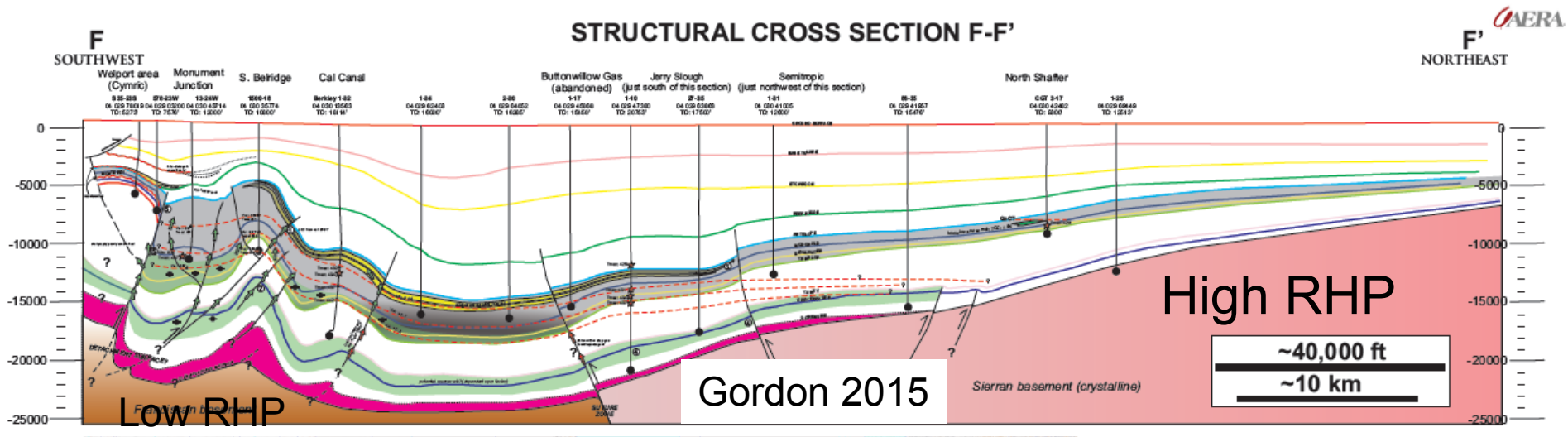
STRUCTURAL CROSS SECTION F-F'

High RHP

Low RHP

Gordon 2015

~40,000 ft
~10 km

Acoustic Basement

Franciscan

N

=

ftp://ftp.consrv.ca.gov/pub/oil/publications/Datasheets/Dtashee
pdf

Crustal Layering Model

- Calculates the basal heat flow based on a "stable" (non-thinning) crust and mantle over time

- Incorporates the U, Th, and K content of the rock type

- Considers transient effects resulting from burial and uplift of the basin fill, e.g. strong subsidence causes a decline in both basal and surface heat flow, uplift would result in an increasing heat flow

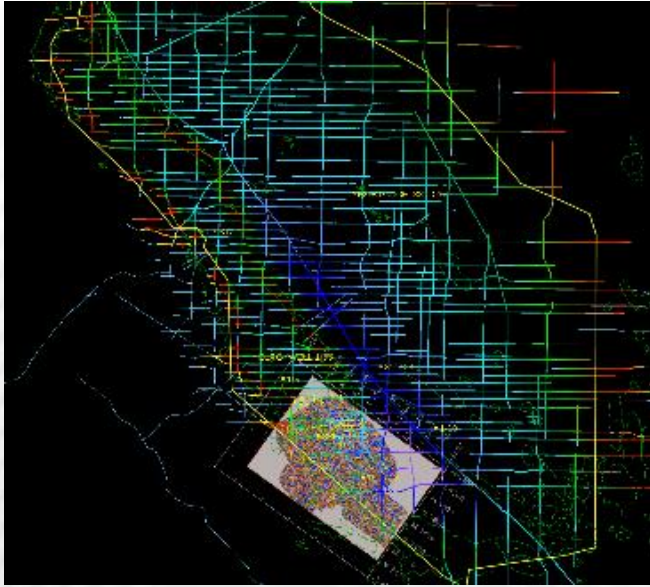- **Does _not_ allow a spatial variation of radiogenic heat production.**

We need to modify the basement manually!!
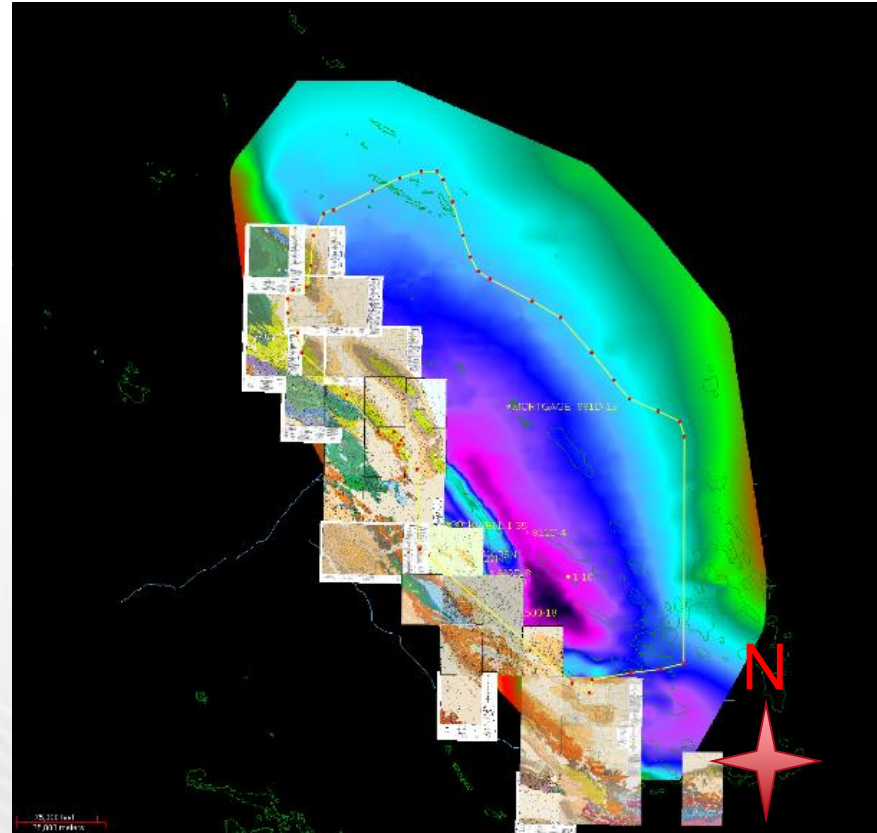
Merged Basement and horizons

Franciscan

Granite
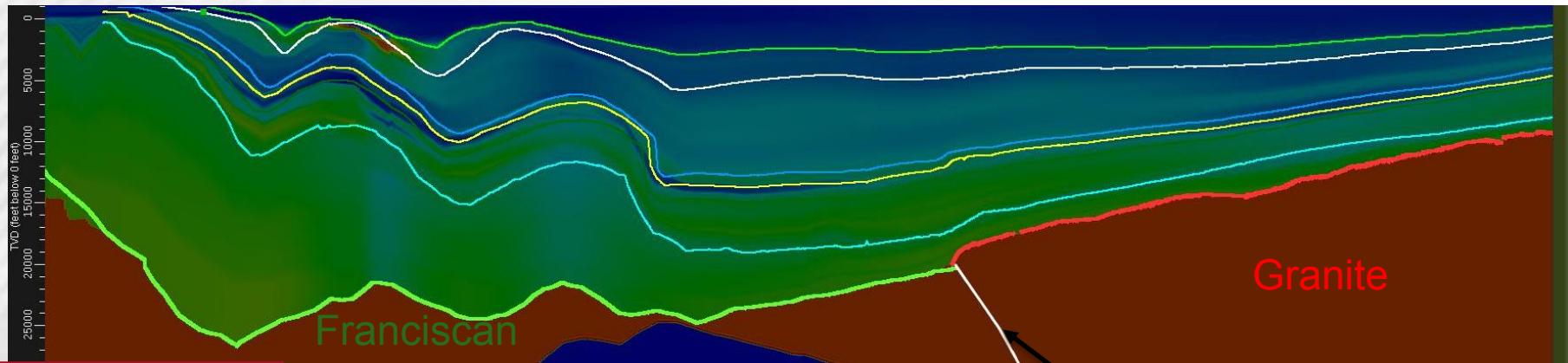
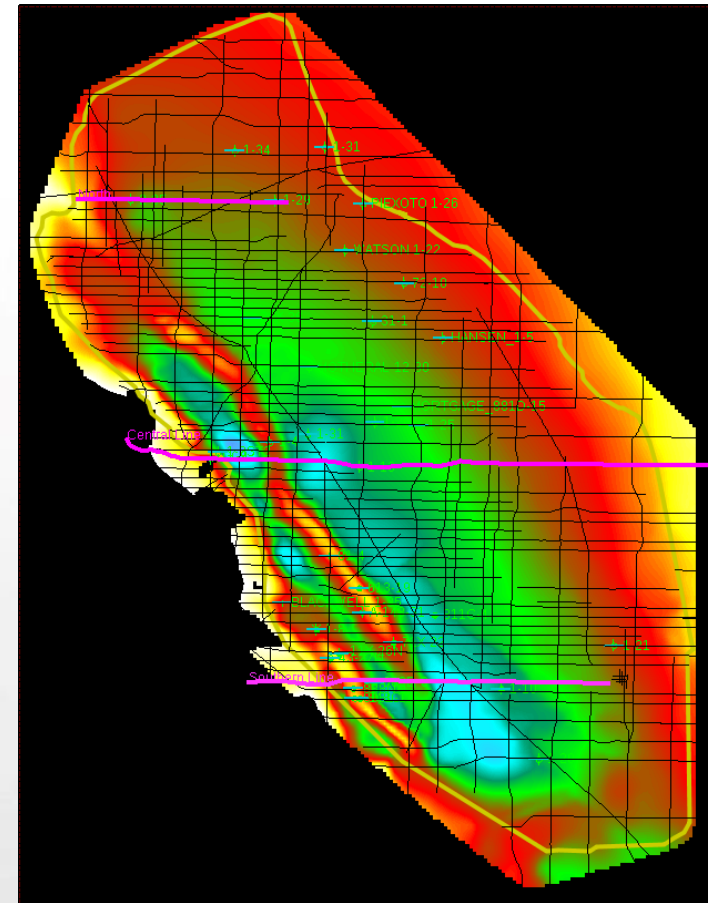Basement Suture

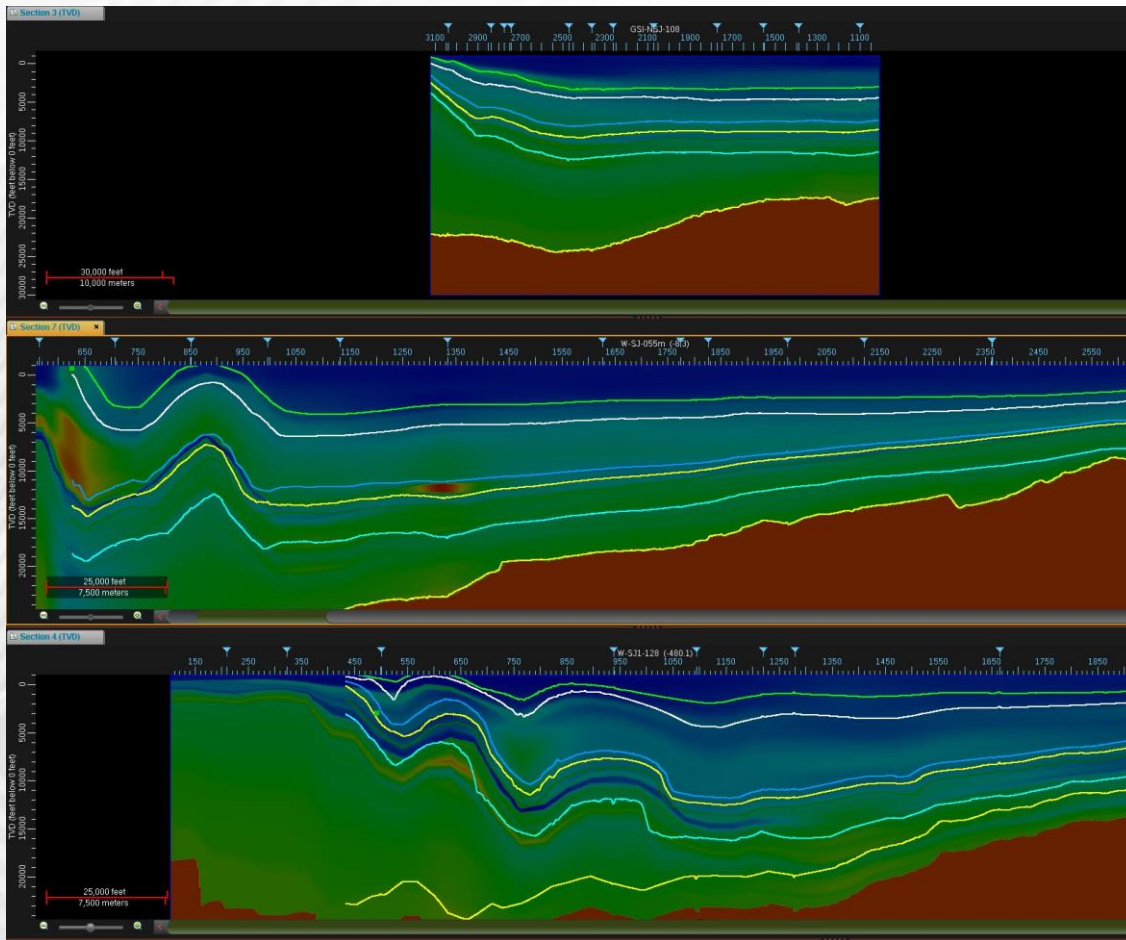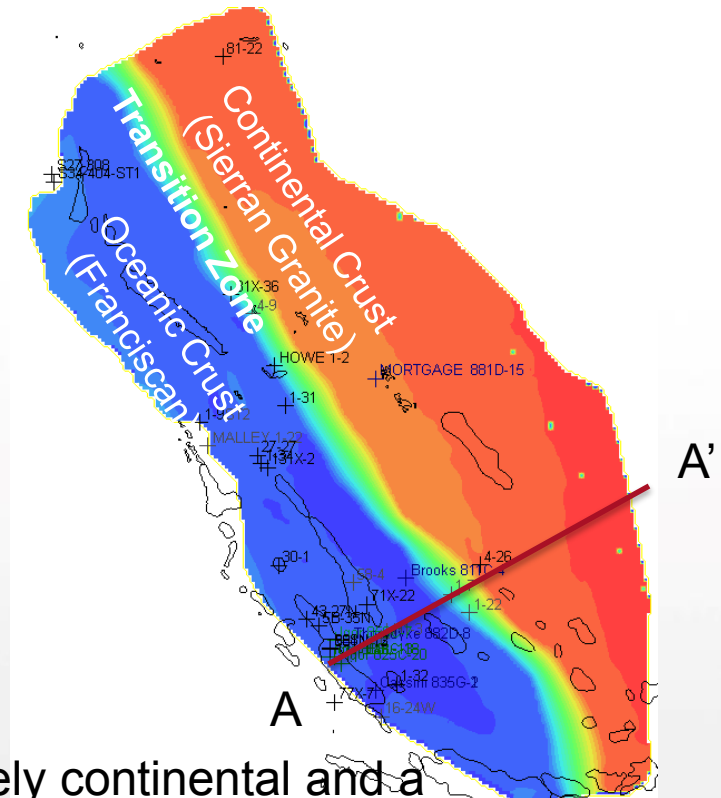# What we did and how we did it
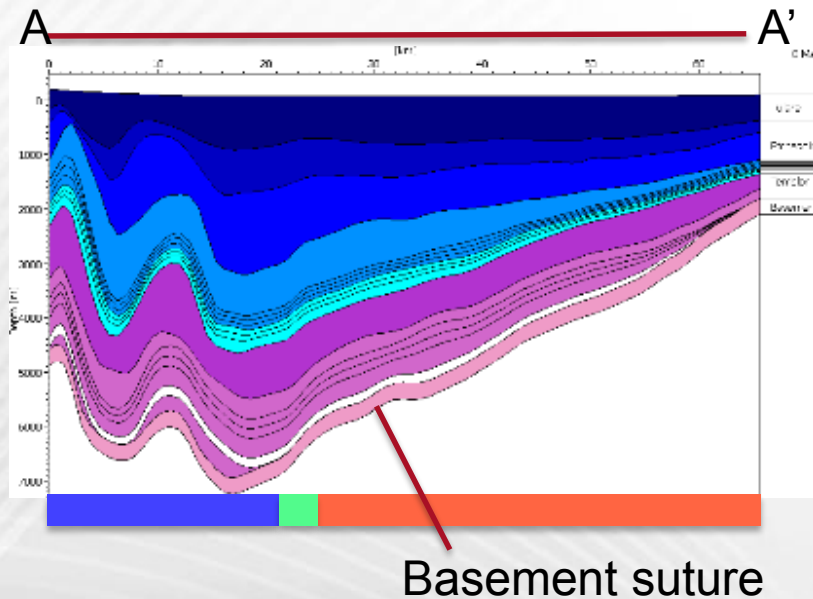

2D

+

Outcrop maps

Resulting basin geometry

Manually modify RHP in PetroMod basin model

Basement suture

- Create end-member scenarios with a purely continental and a purely marine crust

- Establish basal heat flow maps through time resulting from both scenarios
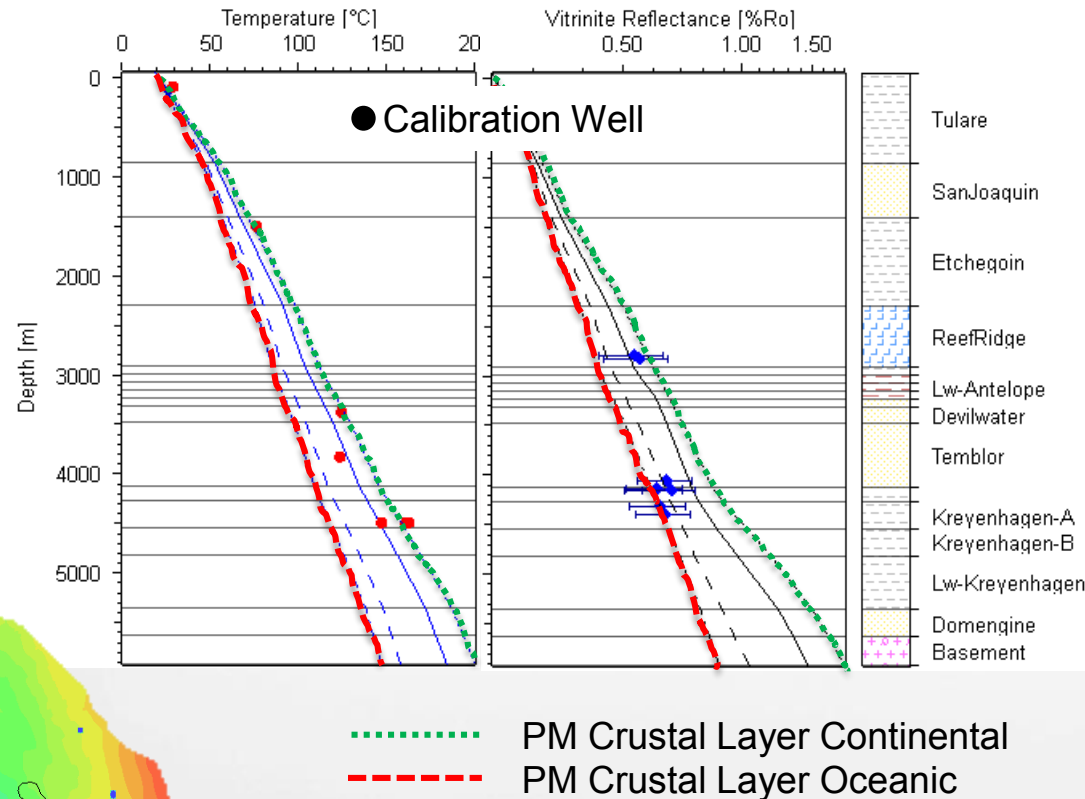
Results: Continental vs Oceanic Crust

Heat Flow Maps [mW/m^2]

Oceanic Crust

min: 34.90
max: 39.70

Continental Crust

min: 51.50
max: 55.40

Too cool

Too warm

● Calibration Well

·········· PM Crustal Layer Continental
– – – – – PM Crustal Layer Oceanic

→ The SJB basement is somewhere in the middle with respect to Radiogenic Heat Production and resulting HF.

Workflow

- Manually splice the heat flow maps to mimic the continental "hot" crust in the east and the oceanic "cool" crust in the west with a transition zone between the two crust types

- Use the resulting maps as basal HF input data for the final basin model

Results: Incorporating variable basal heat flow into the basin model

The crustal models include exclusively continental, exclusively oceanic, a spliced model of oceanic on the west to granitic on the east, and an intermediate crust which uses a 50/50 mix of oceanic and continental radiogenic heat production.
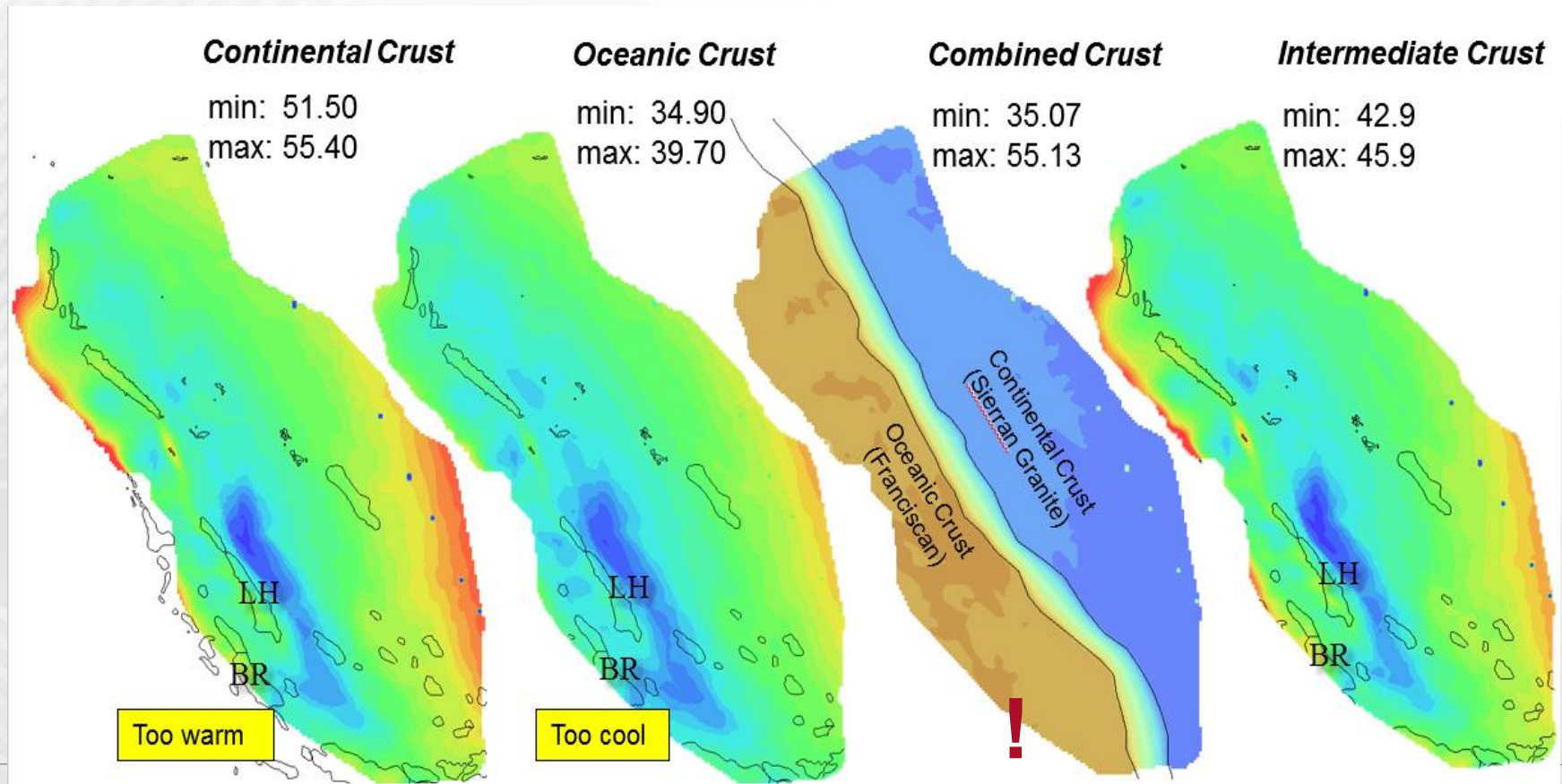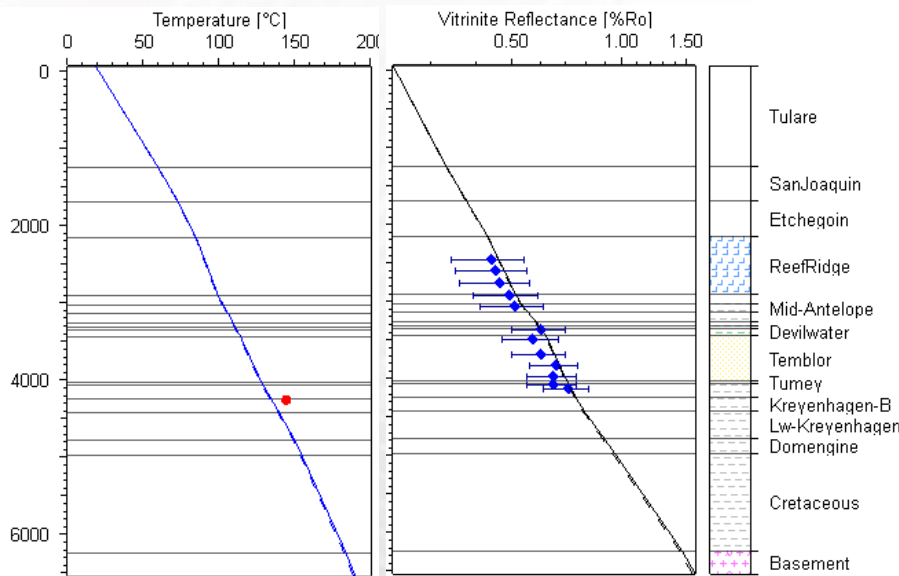
Results: Calibration to wells

Combined Crust
Min: 35 mW/m^2
Max: 55 mW/m^2

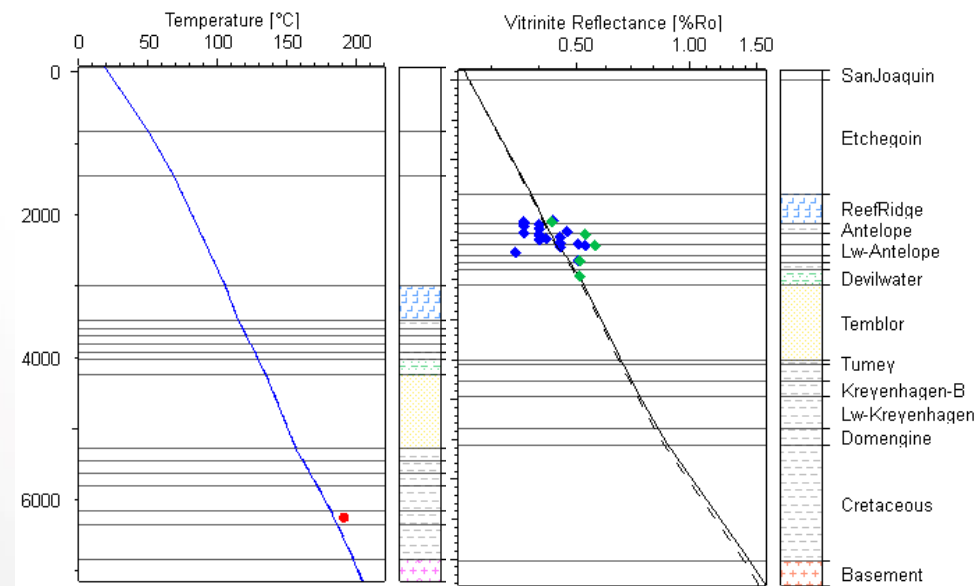○ On-structure Wells
● Off-structure Wells
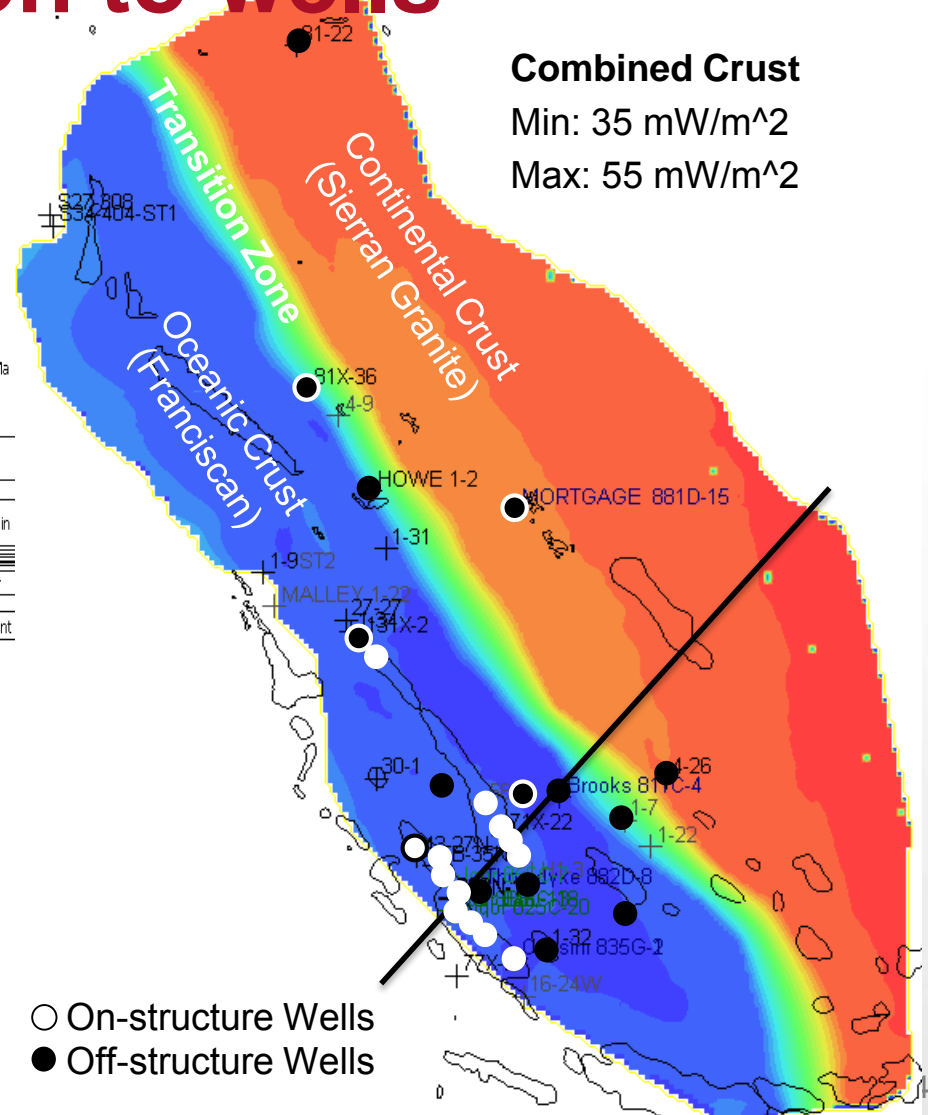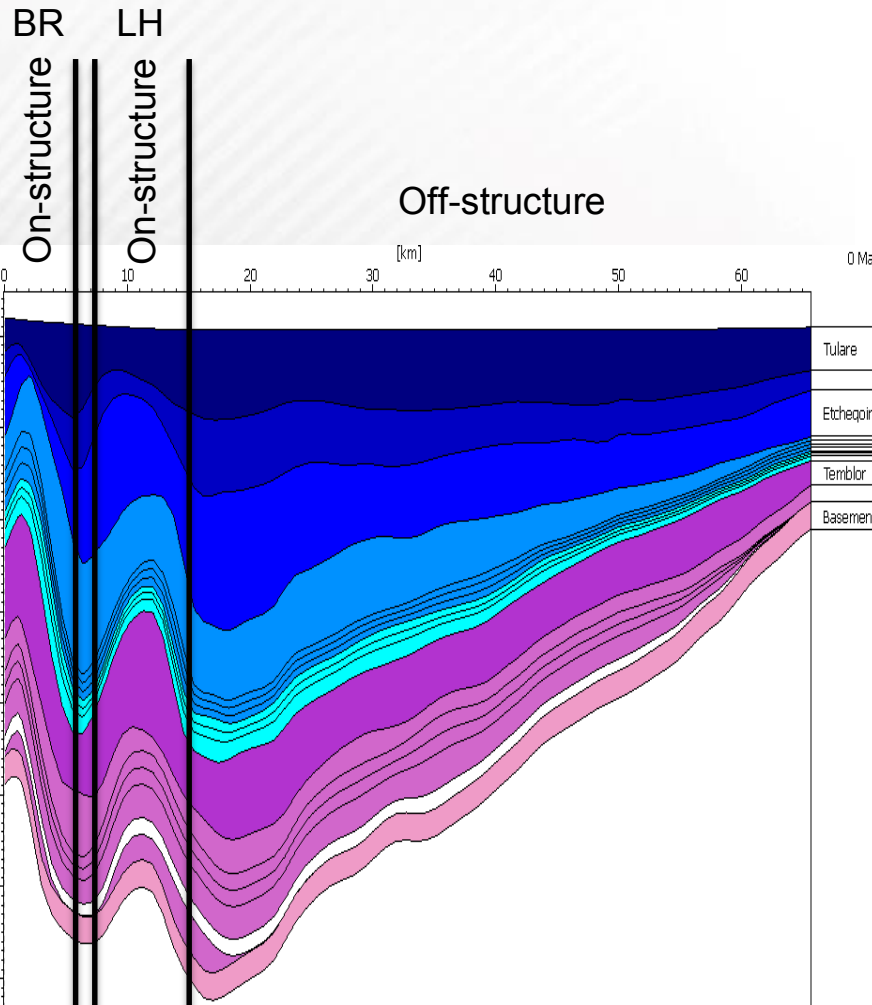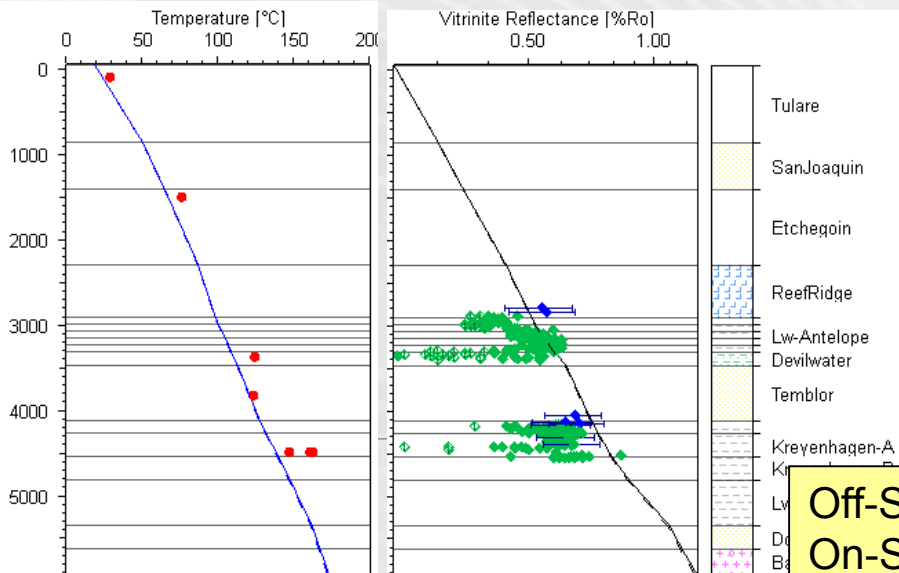
Results: Off and On structure calibration
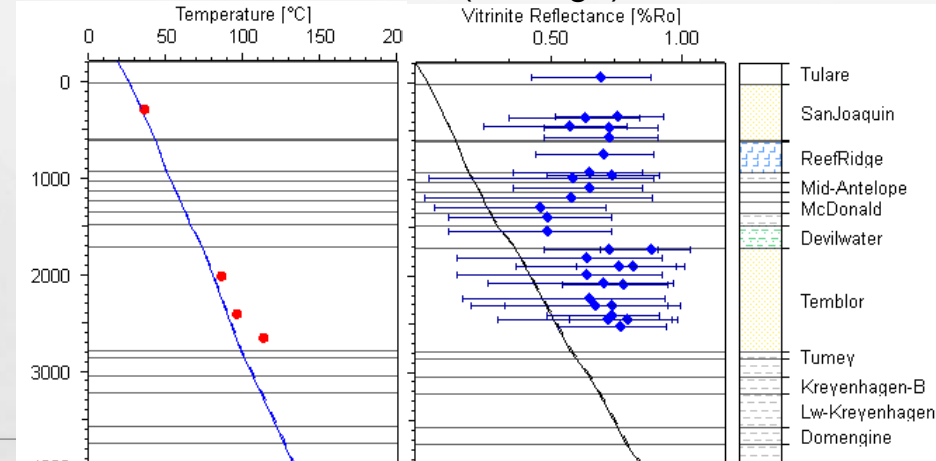

Off-Structure (Transition Zone)

Off-Structure (Oceanic Crust)

Off-Structure (Continental Crust)

On-Structure (Belridge)

Off-Structure: Ro fits, T is (slightly) underestimated
On-Structure: both Ro and T are underestimated

Summary

Crustal Model:

- The key to addressing a comprehensive thermal history for the SJB is to account for the different types of crust of the basin.

- A stable (non-thinning) continental crust (eastern portion of the basin) and an oceanic crust (western portion of the basin) with a transitional zone between the two crust types were modeled to establish a basal heat flow history.

Calibration:

- QC'ed wells and measured well data were used for calibration. Ro was favored over T...

- Off-structure wells were suitable for calibration - the data largely reflects a basal conductive heat flow.

- In the On-structure wells (Belridge, Lost Hills), comparison to calculated HF trends show that both Temperature and Vitrinite Reflectance are greatly elevated compared to the Off-structure wells.

- On-structure wells cannot be calibrated with a crustal conductive HF scenario and seem to require (local) elevated HFs on the order of 20 mW/m^2. This is not in agreement with the generally cooler underlying crust (oceanic Franciscan).

- On-structure wells suggest that there might be a different and/or additional source of HF

Discussion

Observed in many basins: mismatch between T and Ro data…

Mechanisms for locally elevated HF:

- Additional sedimentation, erosion and uplift on the order of >1000m and relatively long residual-time at depth would result in paleo-maximum-burial depth, i.e., high maturity was established before uplift/present-day.
  However, that does *not* account for the high present-day temperatures!

- Local rifting event(s) might have caused higher/early maturation.
  Does *not* account for high present-day T!

- Basin-scale hydrothermal groundwater flow, both along faults and up-structure. This could account for elevated Ro *and* T.
  Convective HF would be an addition (overprint/enhancement) to conductive basal HF.
  Most likely?

Thank You …

- Aera Energy:

  Deborah Edgerton

  Greg Gordon

  Gary Myers

  Dan Schwartz

  Özkan Huvaz

- Schlumberger PetroMod Group:

  Thomas Fuchs and Daniel Palmowski

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[2] Aera Energy LLC, 10000 Ming Ave, Bakersfield, CA 93311 laalpert@aeraenergy.com

Questions?

Thank you!