Integrated basin-scale thermal modeling

Ketil Hokstad, Rune Kyrkjebø, Kenneth Duffaut, Christine Fichler, Zuzana A. Tašárová, Torgeir Wiik, Andrew J. Carter, Eirik Dischler

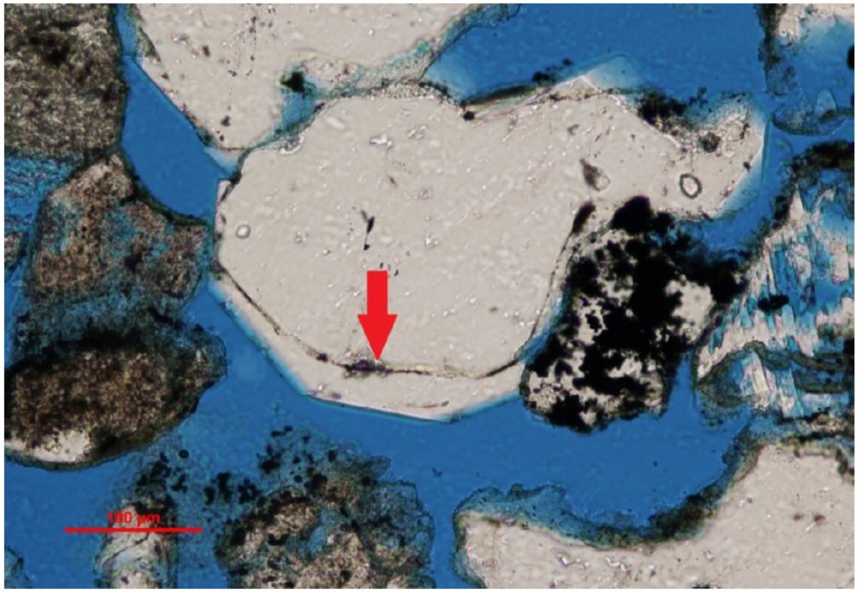
Statoil Research Centre, Trondheim

ROSE meeting, Trondheim, 27. April 2015

Introduction

Temperature history is important for petroleum exploration:

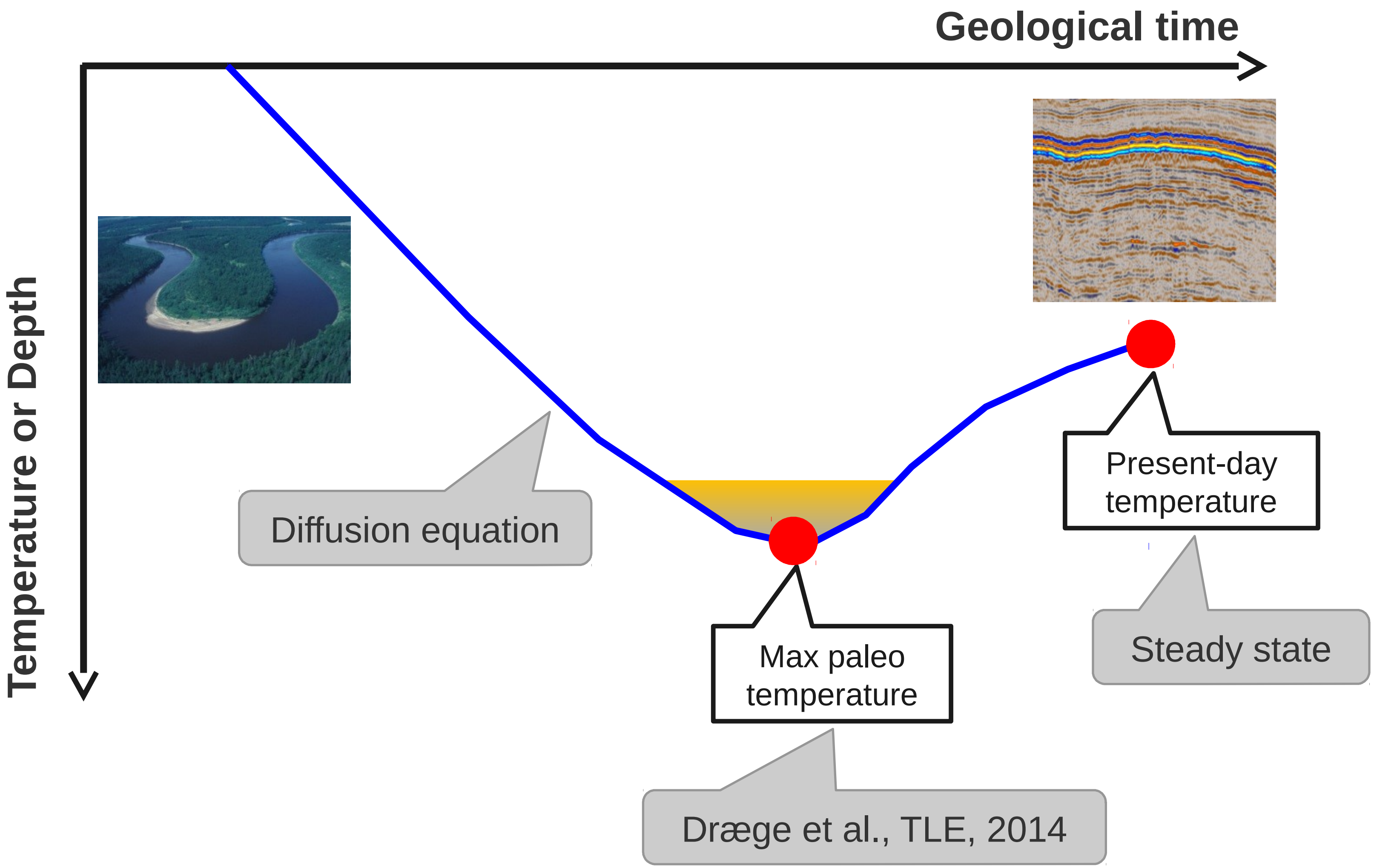
- Source maturation
- Reservoir quality



Example of quartz cementation.

(from Walderhaug-Porten (2012), MSc thesis, NTNU, Trondheim)

Thermal modeling



Statoil

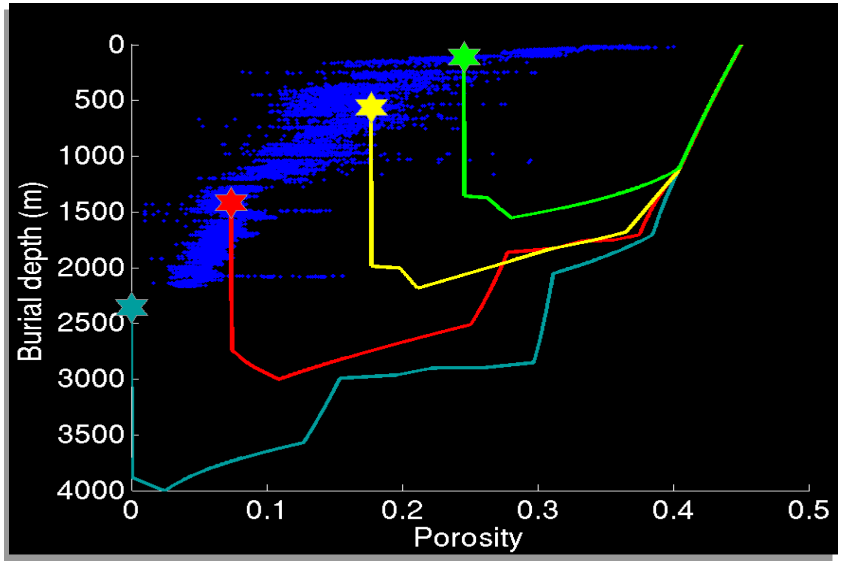
Rock physics model: Underlying principles

- Simplified rock physics model aimed at basin-scale frontier exploration

- Fundamental parameters controling all geophysical parameters (Vp, K, density) are:
  - Porosity
  - Lithology

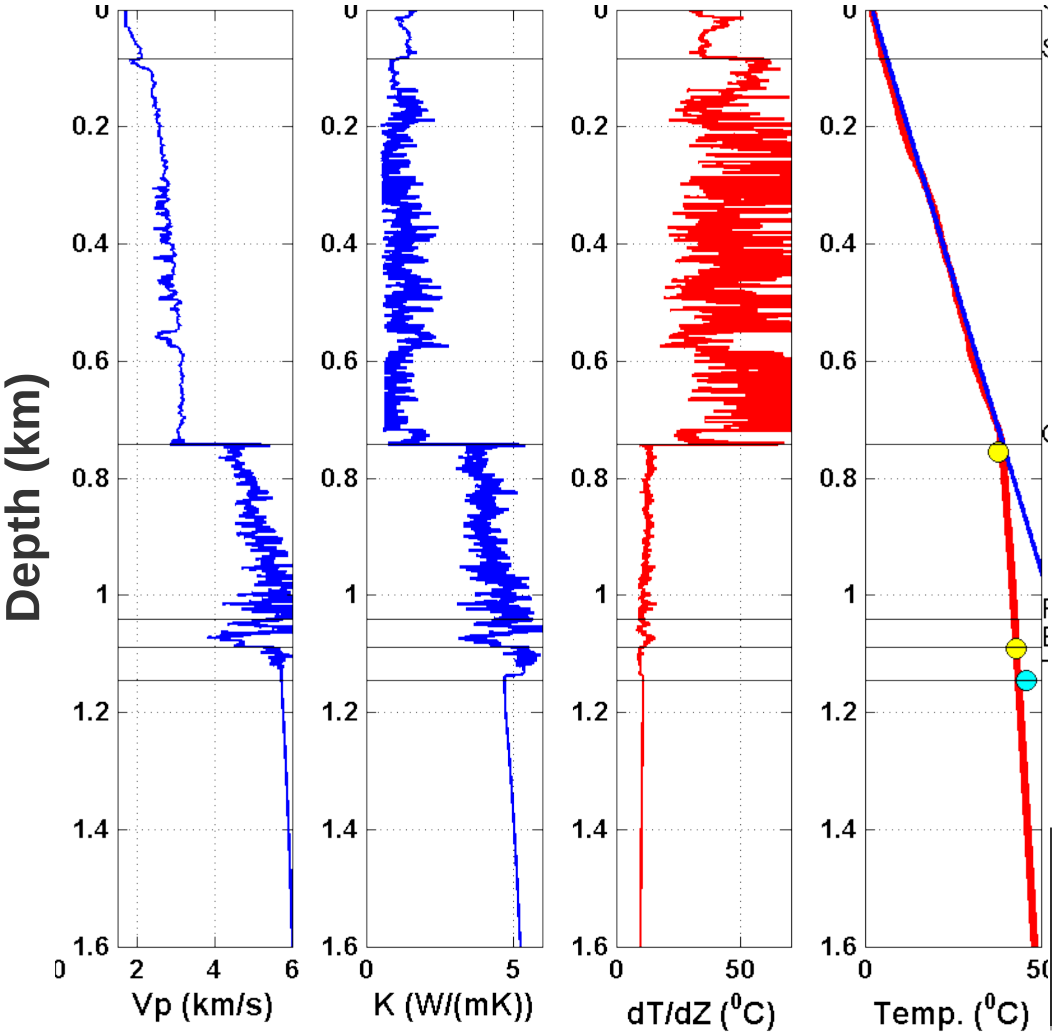
- Rocks have «memory»

Rocks have ‘’memory”!



Statoil

Rock physics model : Thermal conductivity

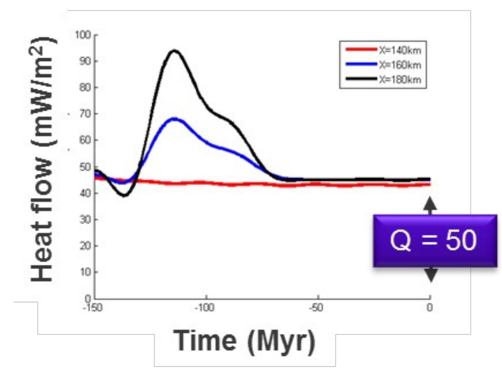


- Heat conductivity (K) :

$$K = a(L)V_P$$

$$V_P = \text{seismic velocity}$$
$$\text{„}L = \text{"lithology parameter"}$$

Adapted from Rybach (1997)



50 ^{0}C/km
Rock physics model
o MDT
o BHT 46^{0}C NPD

Some nice consequences of the velocity vs heat conductivity relation

1D Fourier's law in TVD:

$$T(z) = T_0 + q\int_{z_0}^{z} \frac{dz'}{k(z')} = T_0 + q\int_{z_0}^{z} \frac{dz'}{a(L)v_P(z')}$$

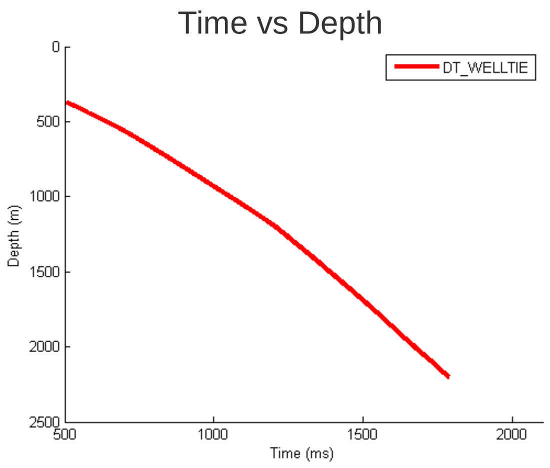
1D Fourier's law in TWT:

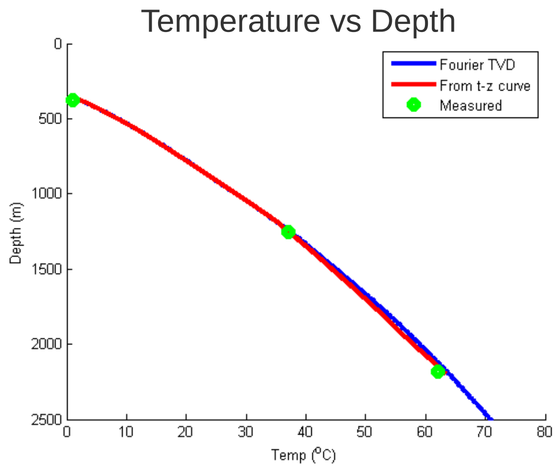
$$T(t) \simeq T_0 + \frac{q}{2\hat{a}}[t - t_0]$$

Temperature vs depth is almost proportional to time vs depth:

$$T(z) \simeq T_0 + \frac{q}{2\hat{a}}[t(z) - t(z_0)]$$

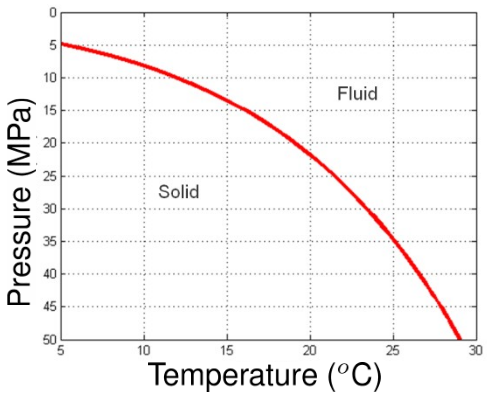
Hokstad (2014): **Improvements in determining subsurface temperatures**, Patent Application WO 2014/173436 A1

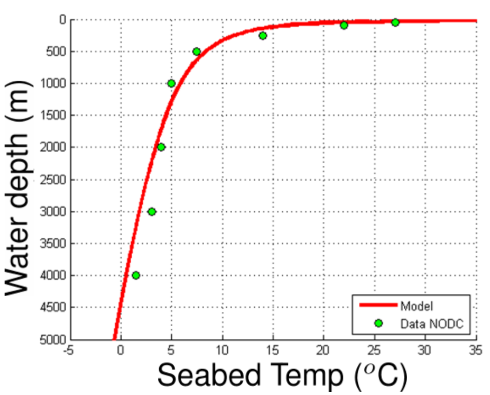


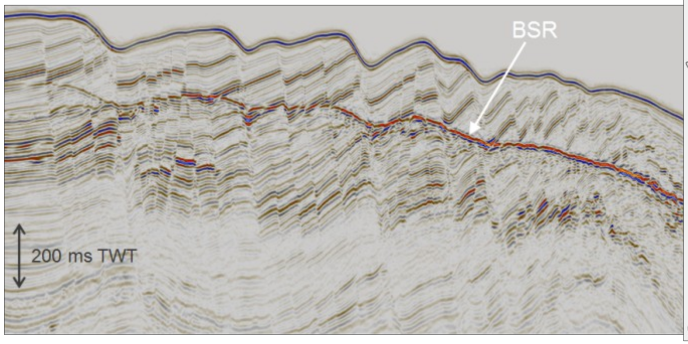


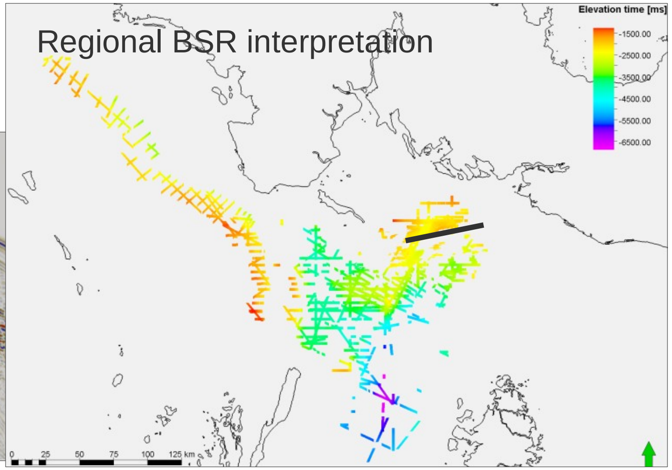
Statoil

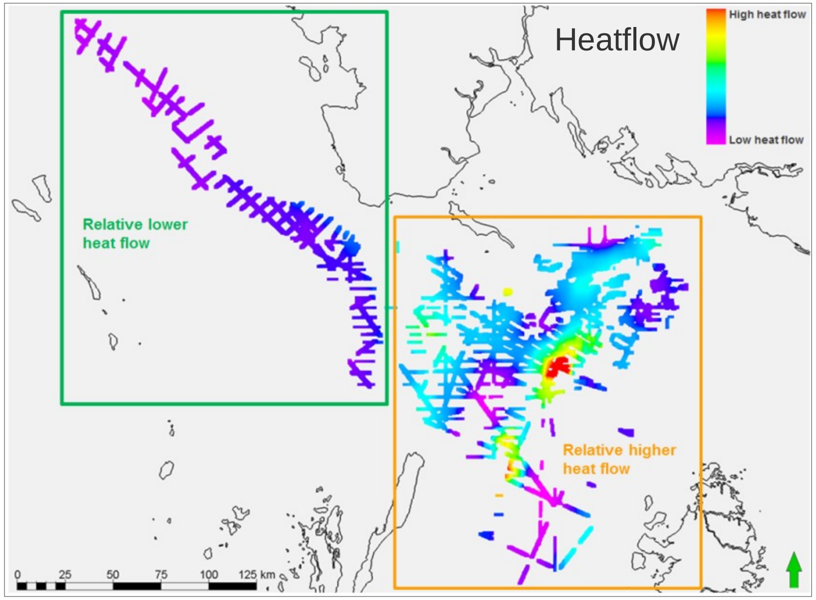
Heatflow estimation from BSR: Examle from West Papua

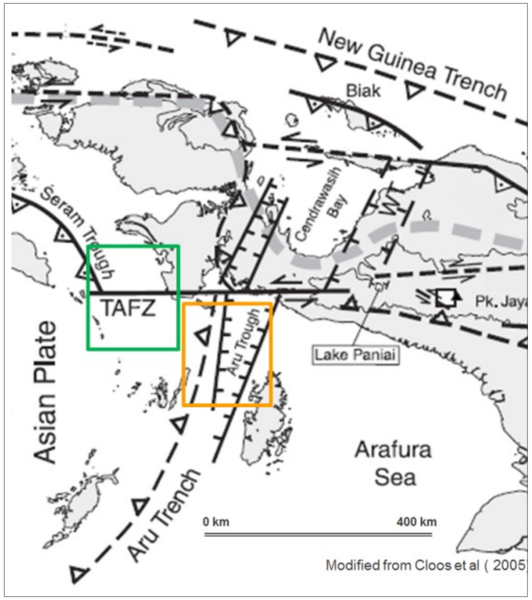






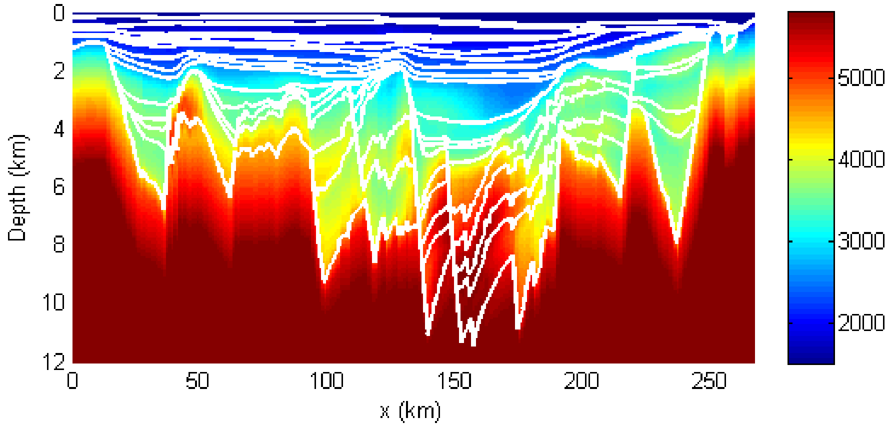


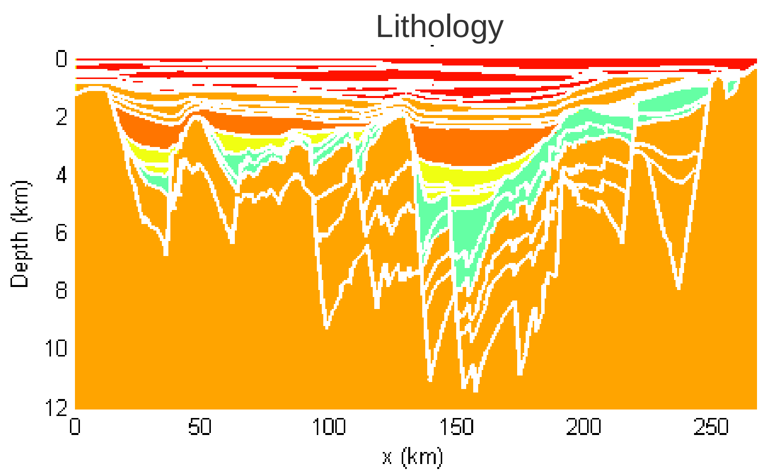


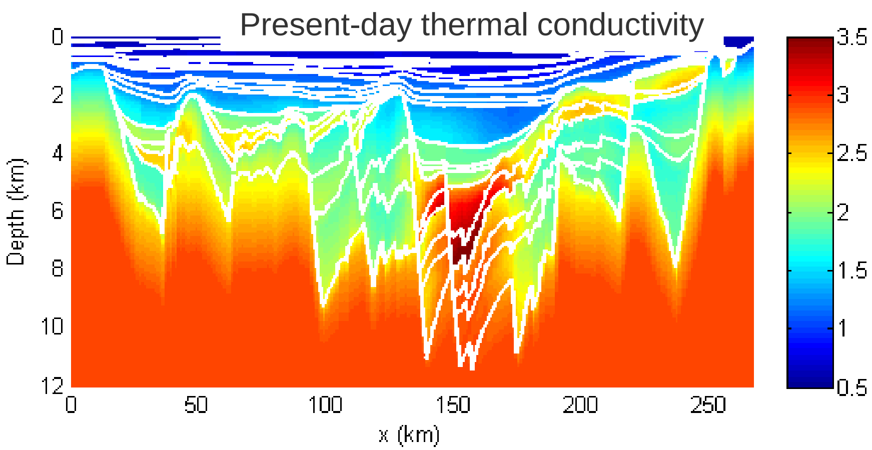


Priyanto, Hokstad, Zwach, V Shaack, Mjøs, Hartadi, Duffaut, Tasarova (2015): **Heat Flow Estimation from BSR: An Example from the Aru Region, Offshore West Papua**, Indonesian Petroleum Association, Proceedings

Thermal conductivity in 2D and 3D







$$K = a(L)V_P$$

Example from NDSP-84-1
Viking Graben, North Sea

Previous work on NDSP-84-1:
- Kyrkjebø (1999)
- Odinsen et al. (2000)
- Christiansson et al. (2000)

Statoil

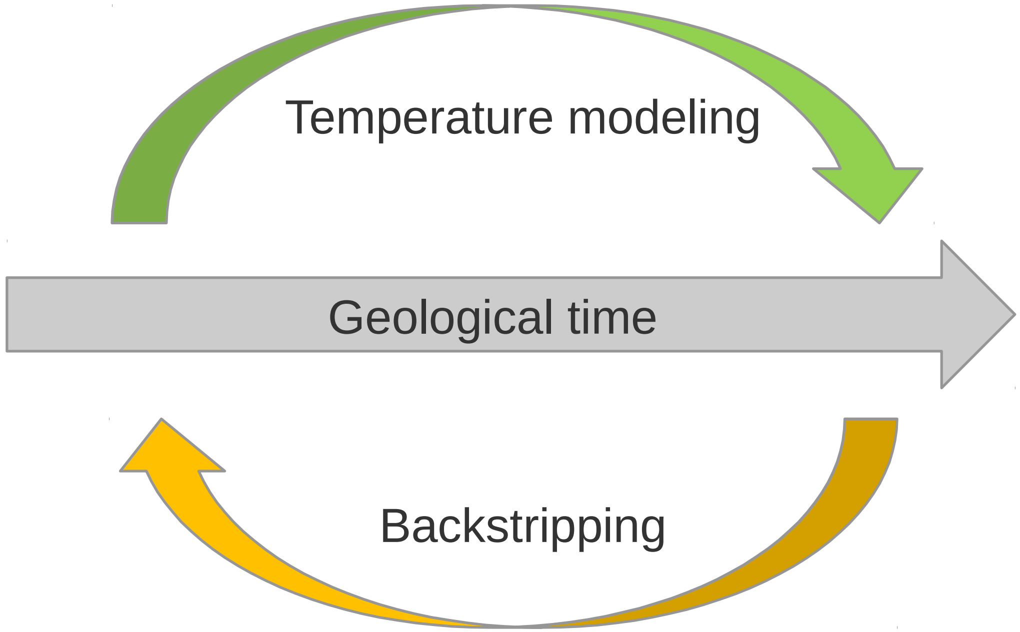
Elements of time-dependent thermal modeling

- Backstripping: (time-reversed geology)
  - Background porosity trend
  - Heat conductivity
  - Velocity
  - Density

$$\partial_t T + (u - \frac{\partial_z k}{c\rho})\partial_z T = \frac{k}{c\rho}\partial_z^2 T \qquad \text{1D}$$

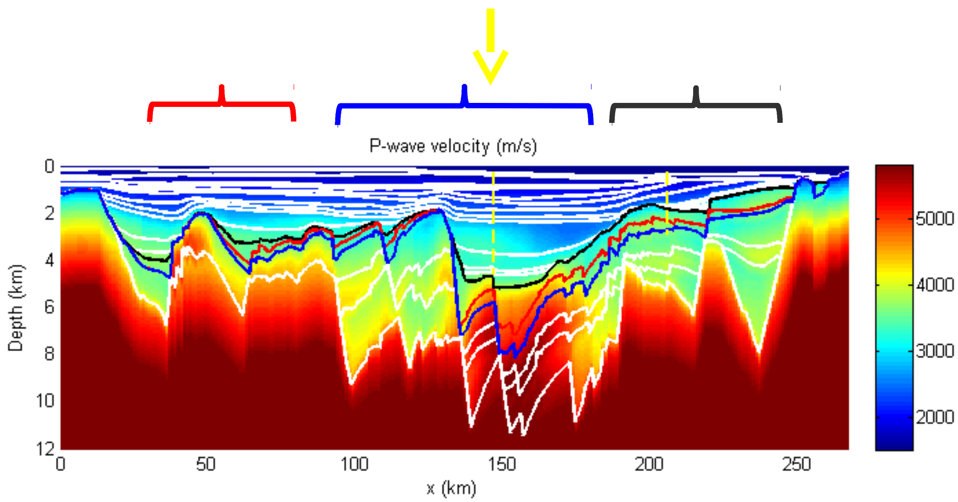
$$\partial_t T + u_i \partial_i T = \frac{1}{c\rho}\partial_i k_{ij} \partial_j T \qquad \text{2-3D}$$

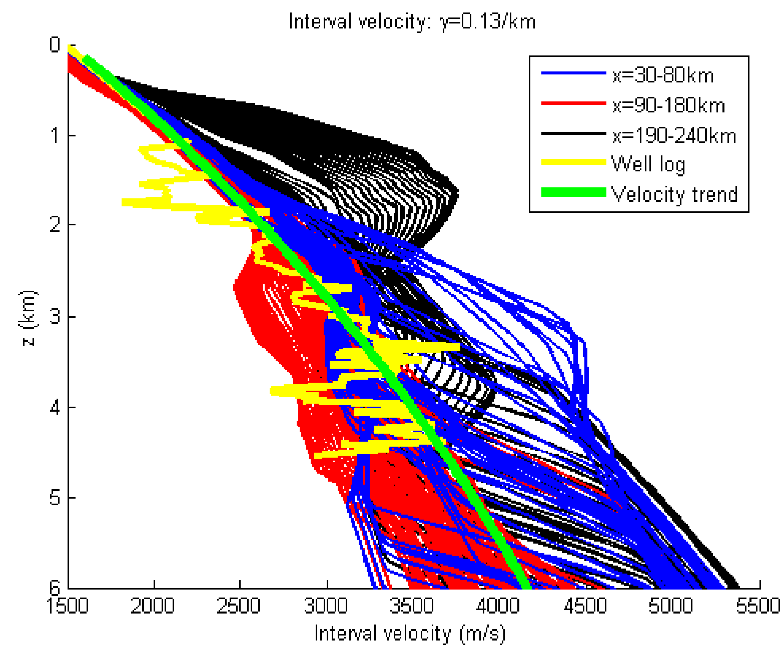
- Basal heat flow history
  - Crustal stretching and thinning
- Solve the heat equation
  - 1D Finite Difference
  - 2D Finite Difference



Hokstad, K. , Wiik, T., Dræge, A., Duffaut, K., Fichler, C., and Kyrkjebø, R. (2014), **Temperature modeling constrained on geophysical data and kinematic restoration:** Patent Application WO/2014/029415

Viking Graben: Macro-trend (compaction curve)





Macro trend is obtained from

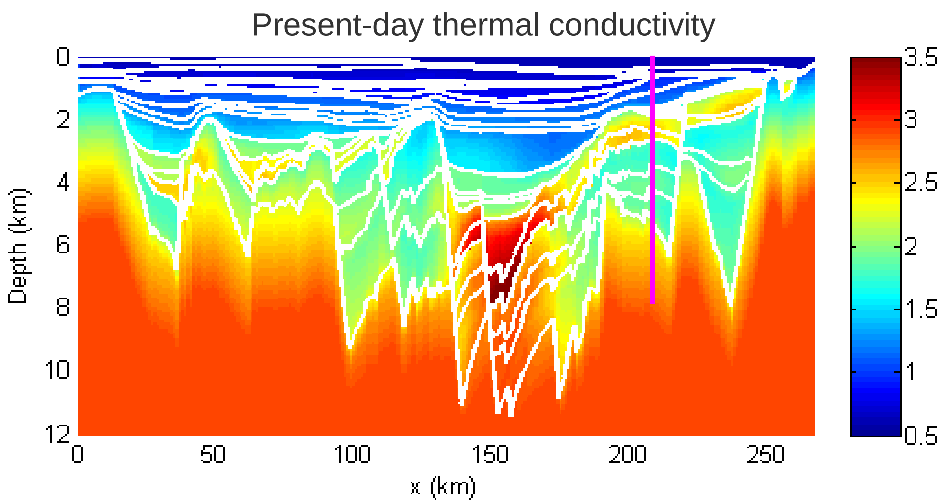
- Seismic interval velocities
- And/or density (gravity modeling)

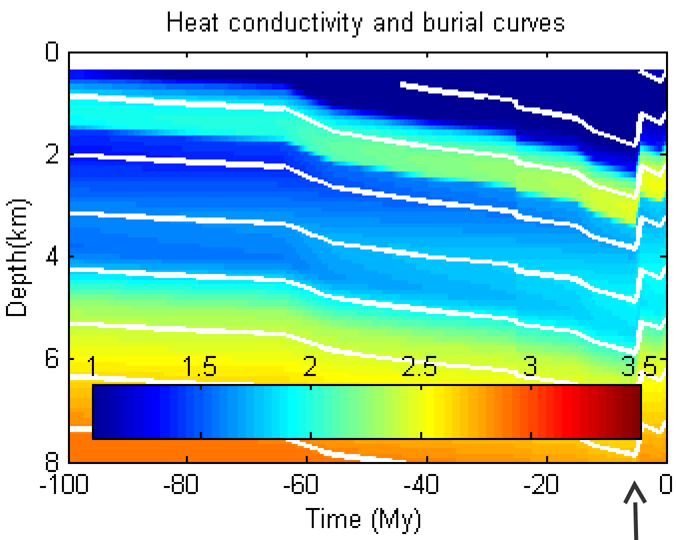
Porosity trend:

$$\phi(z) = \phi_0 e^{-\gamma z}$$

Statoil

Backstripping velocity, density and K

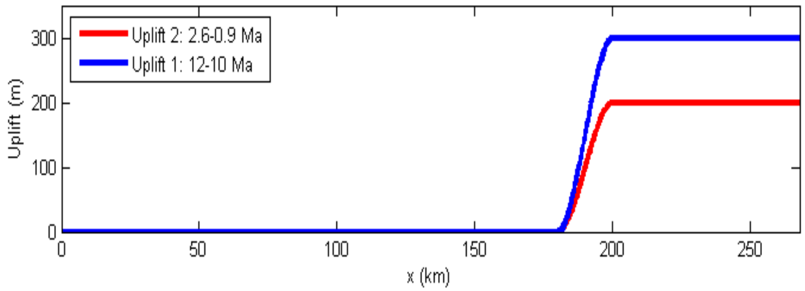




Decompaction

Frozen

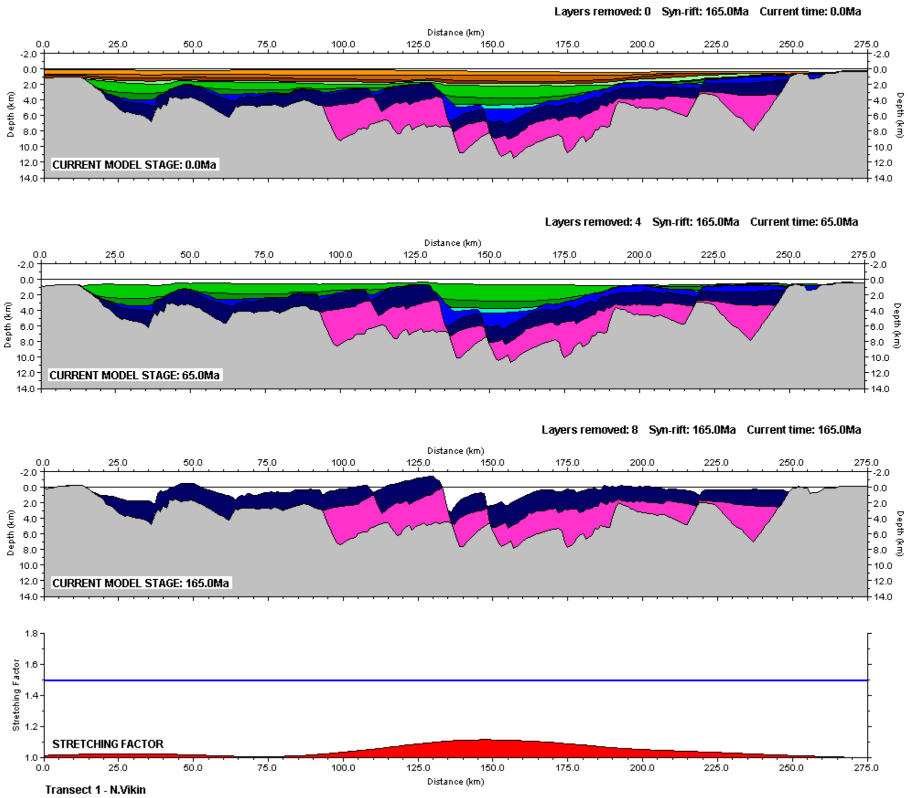
Time of maximum burial



Two episodes of Neogene uplift (=erosion) in the east

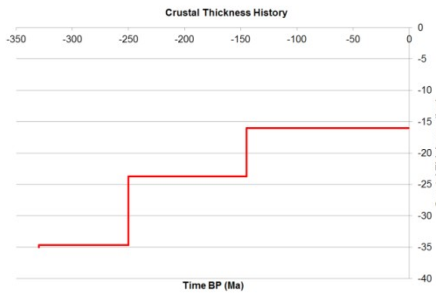
Statoil

Viking Graben: Basal heatflow history

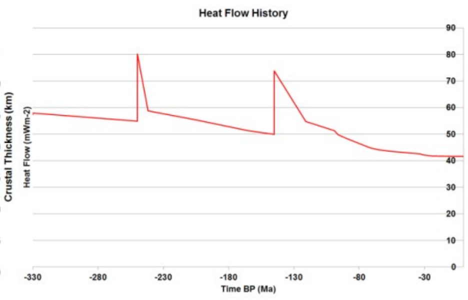


Tectonic restoration – β-factors

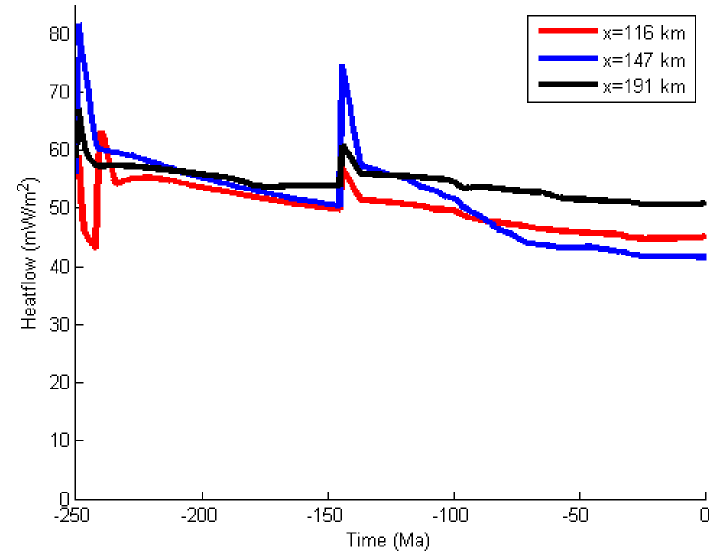
Rune Kyrkjebø (1999); PhD Thesis



Crustal thickness

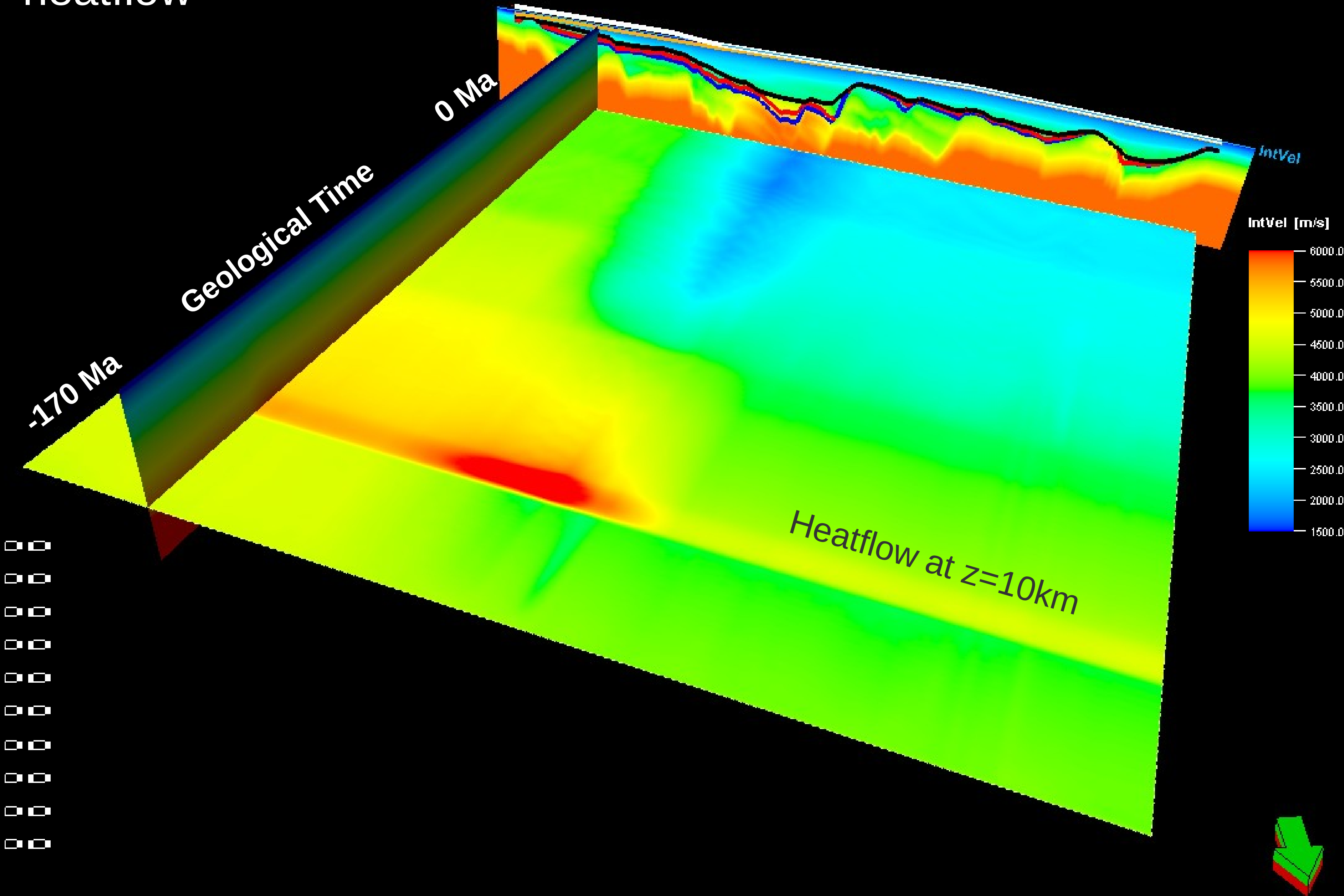


Basal heatflow

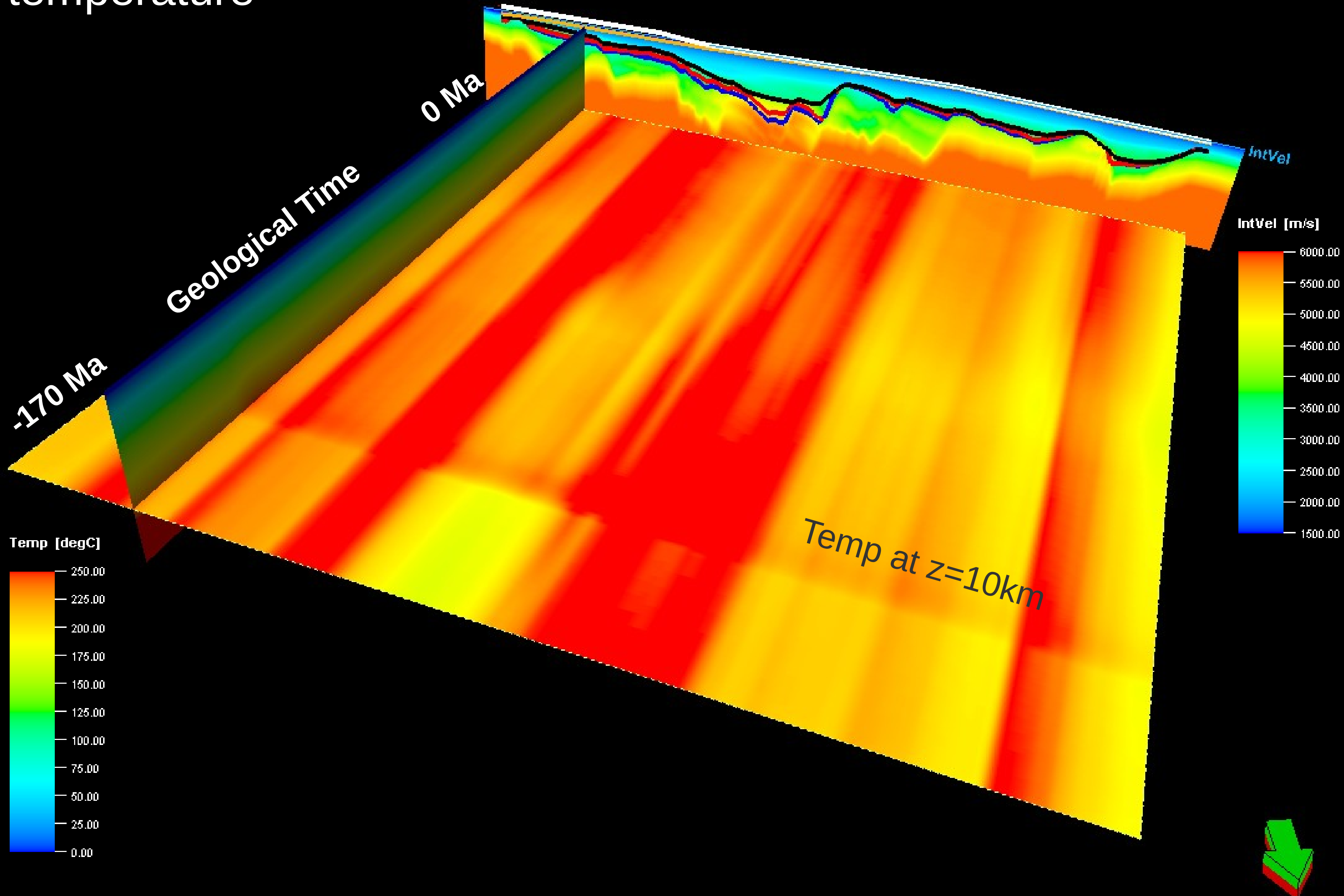


Statoil

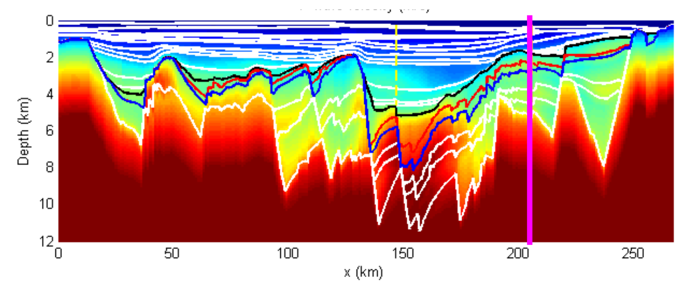
Seismic velocity and heatflow

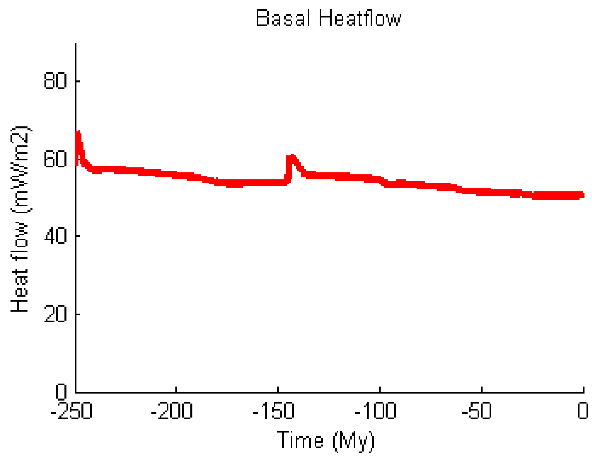


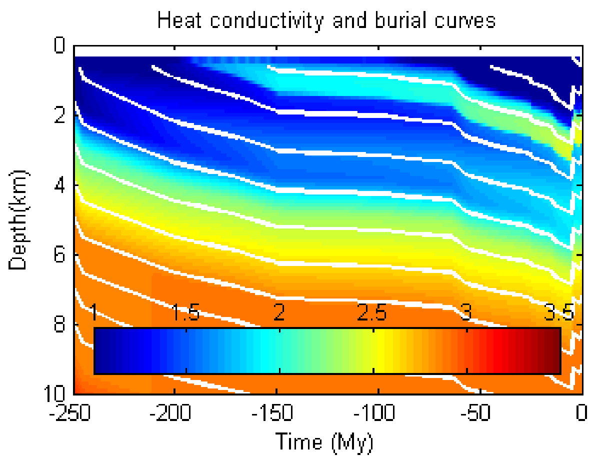
Seismic velocity and temperature

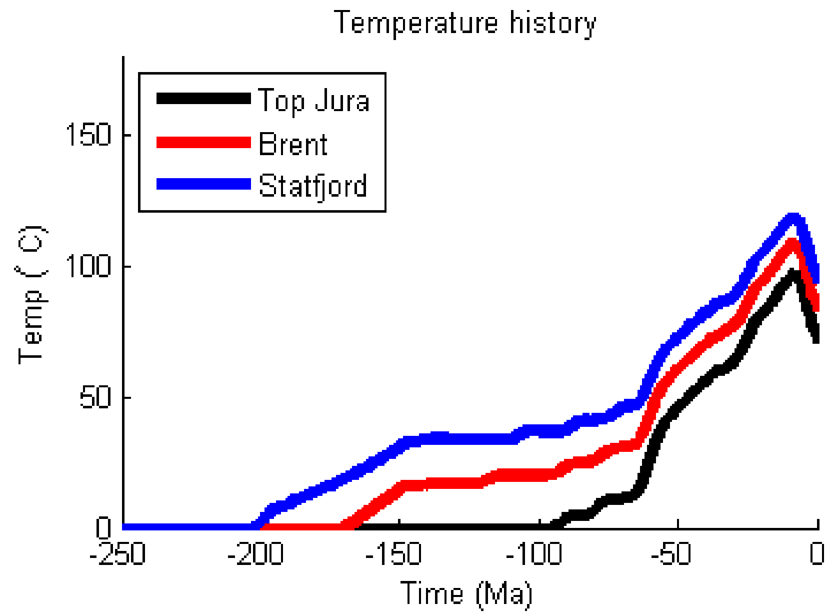


Thermal modeling
Projected well 35/11-7 (500m uplift)

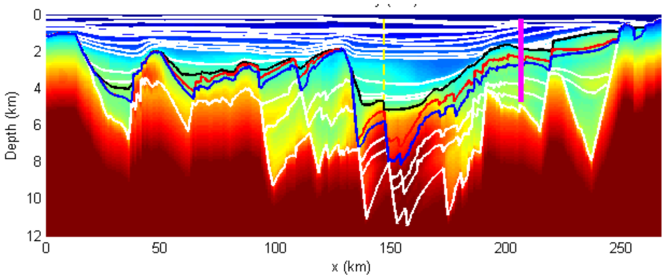


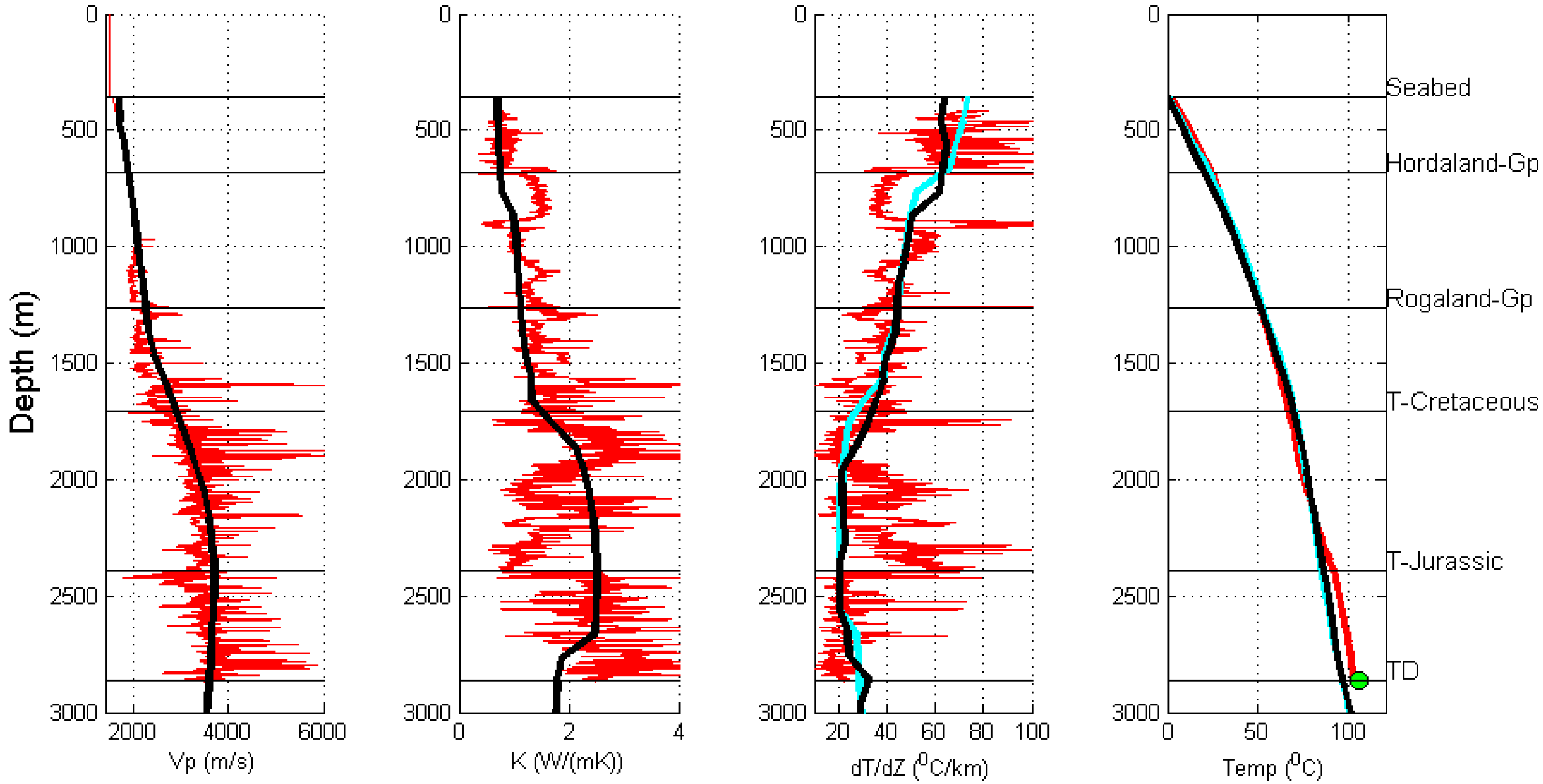






Comparison with well 35/11-7
Troll area

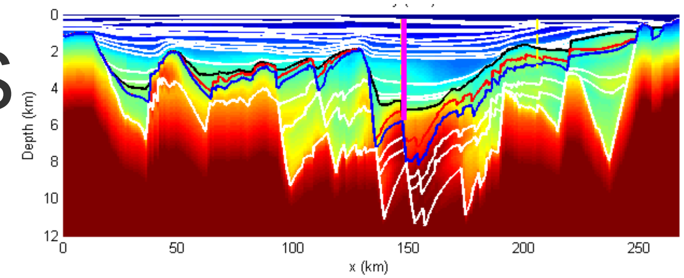


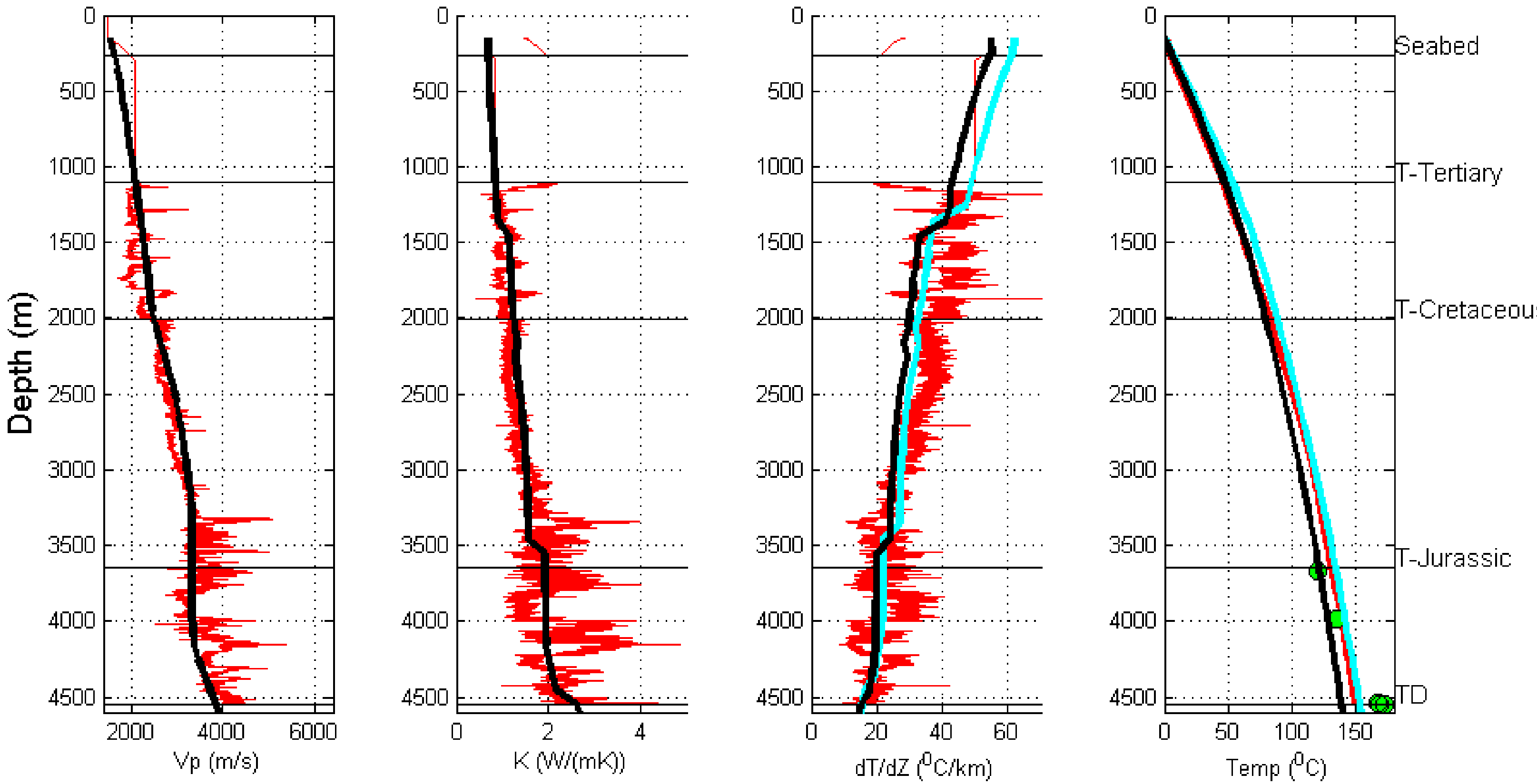


Time dependent: Seismic
Steady state: Seismic
Steady state: Well log

Statoil

Comparison with well 34/11-2S Kvitebjørn

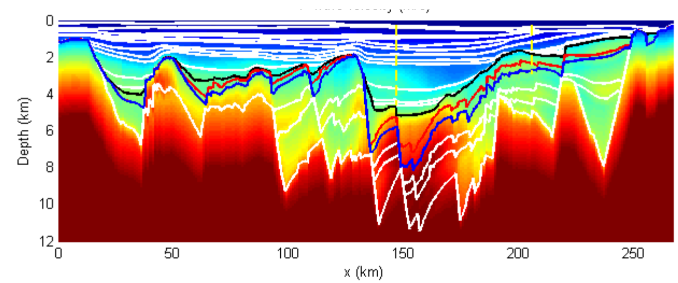


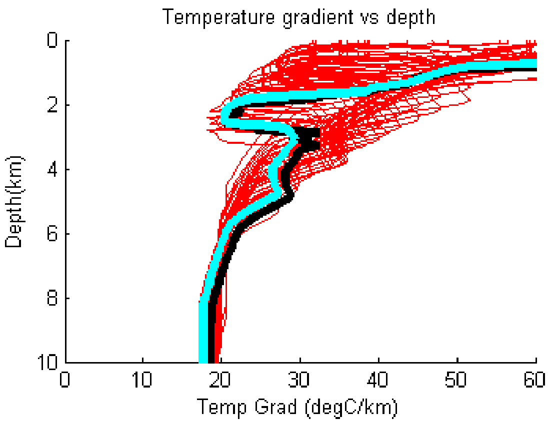


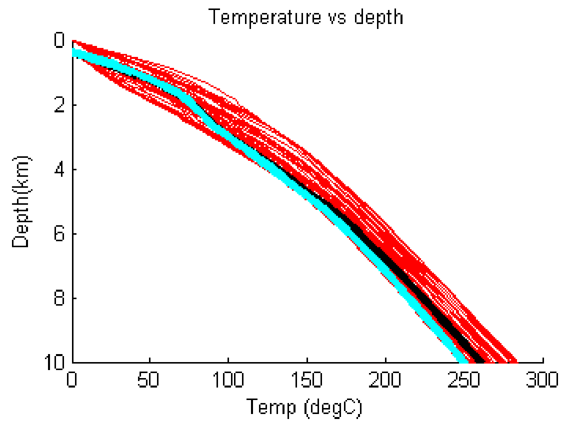
Time dependent: Seismic
Steady state: Seismic
Steady state: Well log

Statoil

Viking Graben: Thermal equilibrium?

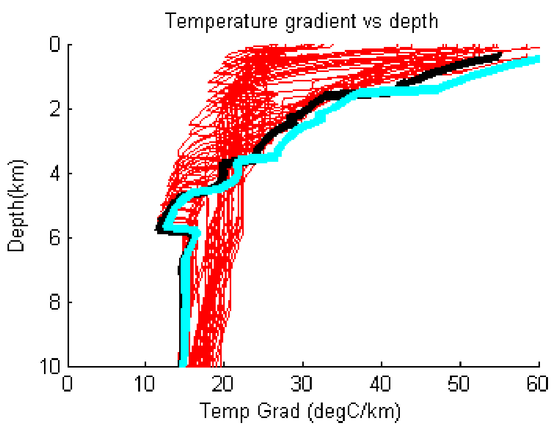


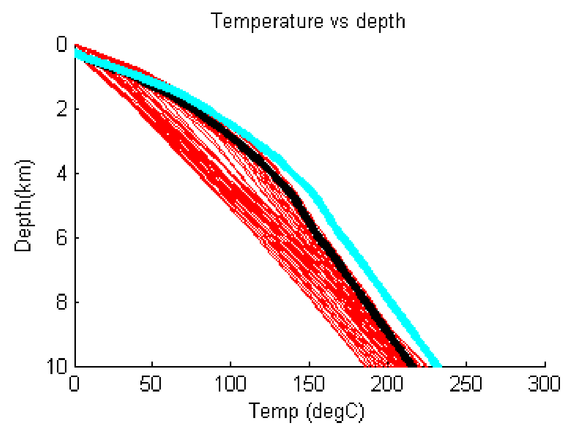




Projected well 35/11-7:

- Aproximately thermal equilibrium
- Neogene uplift and erosion





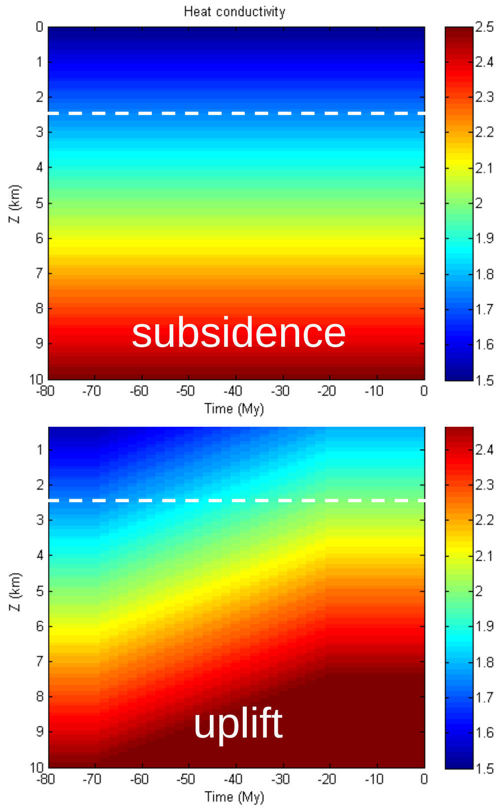
Projected well 34/11-2S

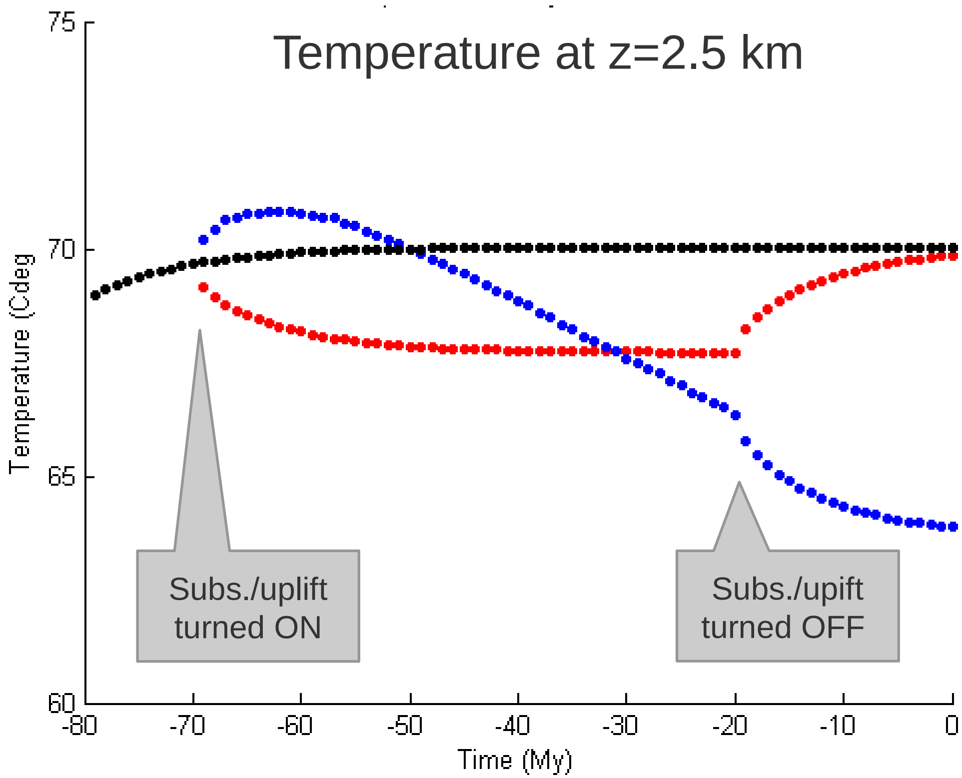
- Not in thermal equilibrium
- Neogene sedimentation
- Pliocene sed.rate: 170 m/Ma

____ Time dependent
____ Steady state

Statoil

Synthetic example: Generic effects of subsidence (sedimentation) and uplift

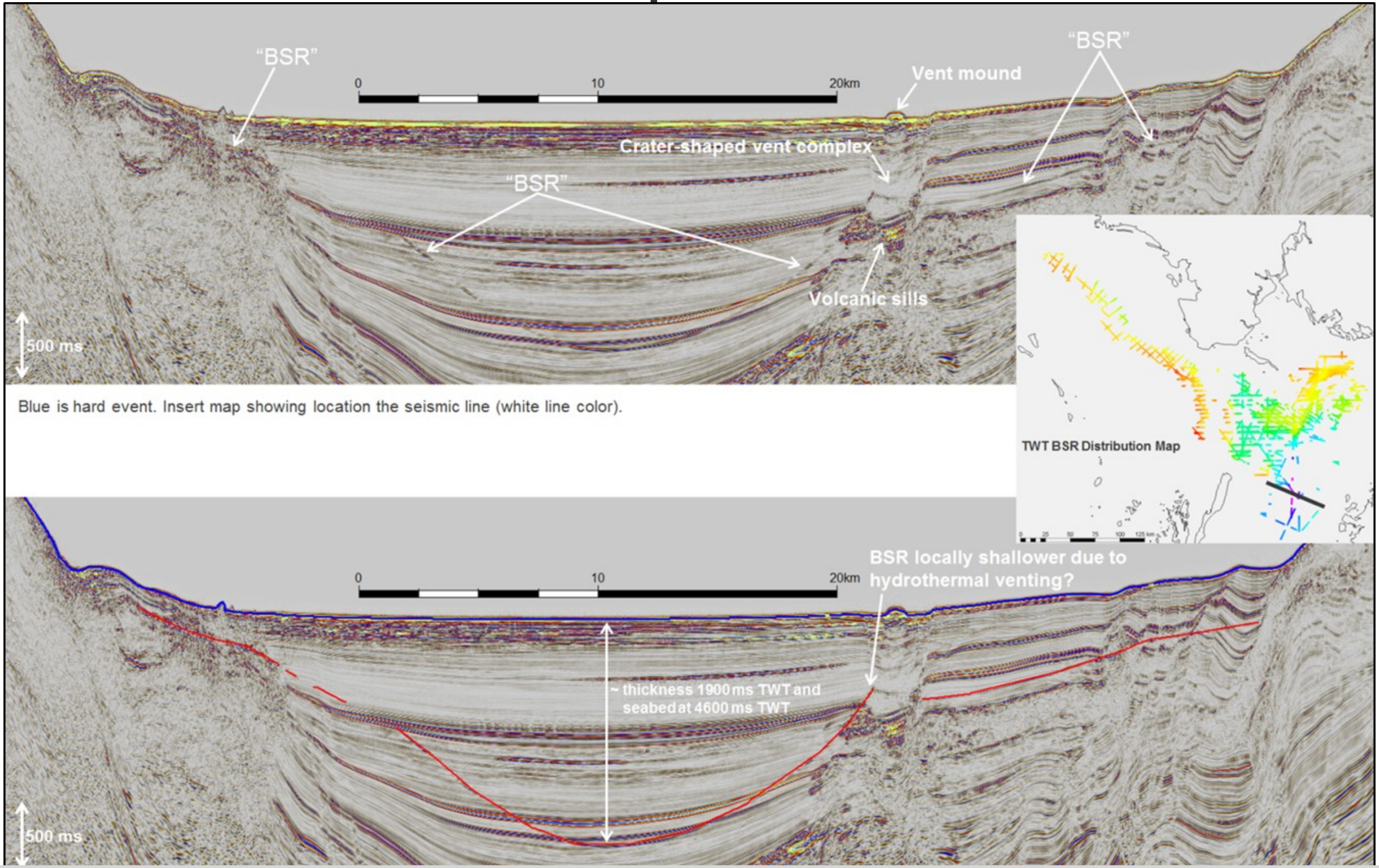




- Subsidence&sedimentation => cooling
- Uplift => first heating; then cooling;
- Effect of advection and changed conductivity

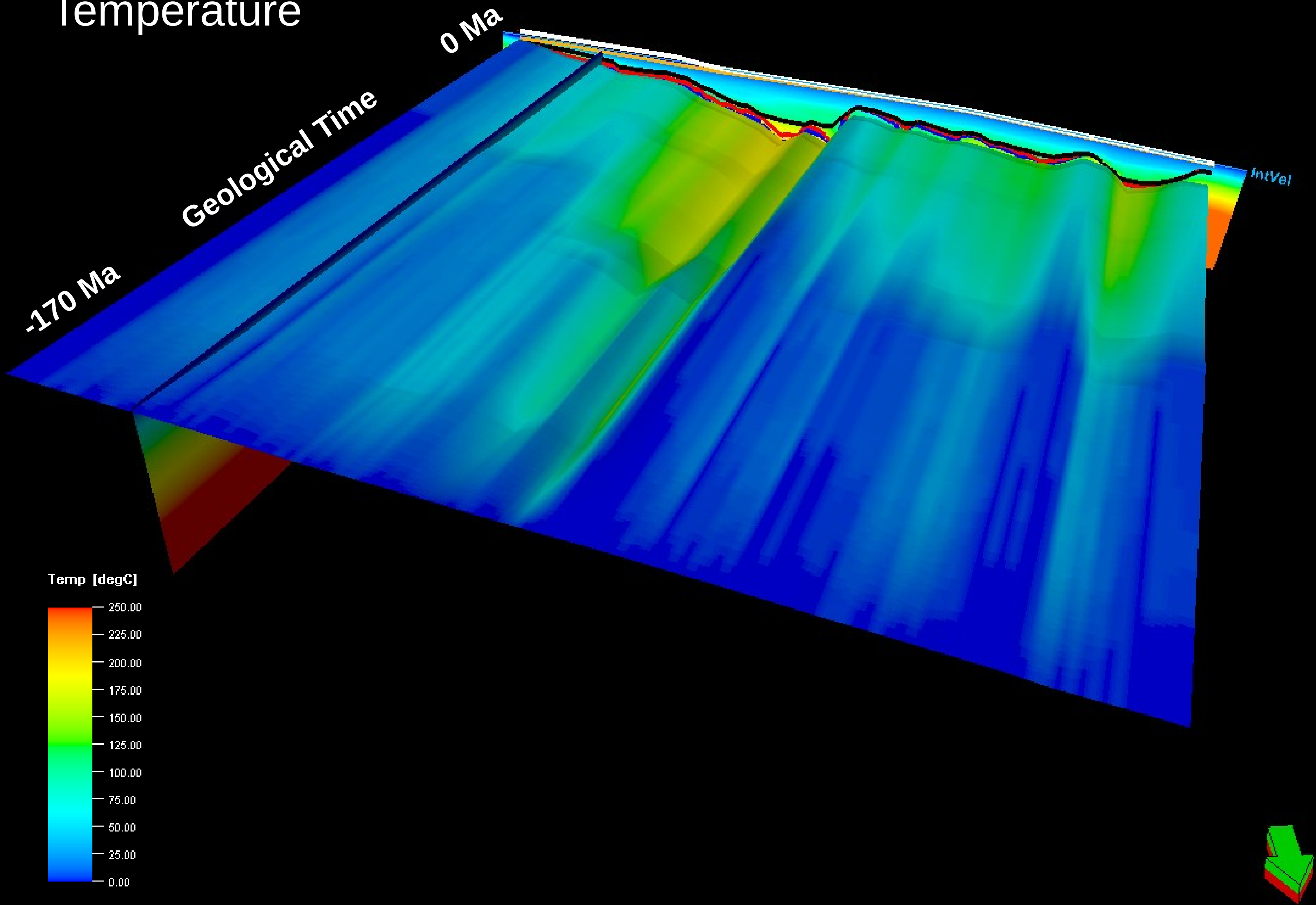
Black: Reference (steady)
Red: Subsidence 50 m/My
Blue: Uplift 50 m/My

BSR deflection:
Examle from West Papua

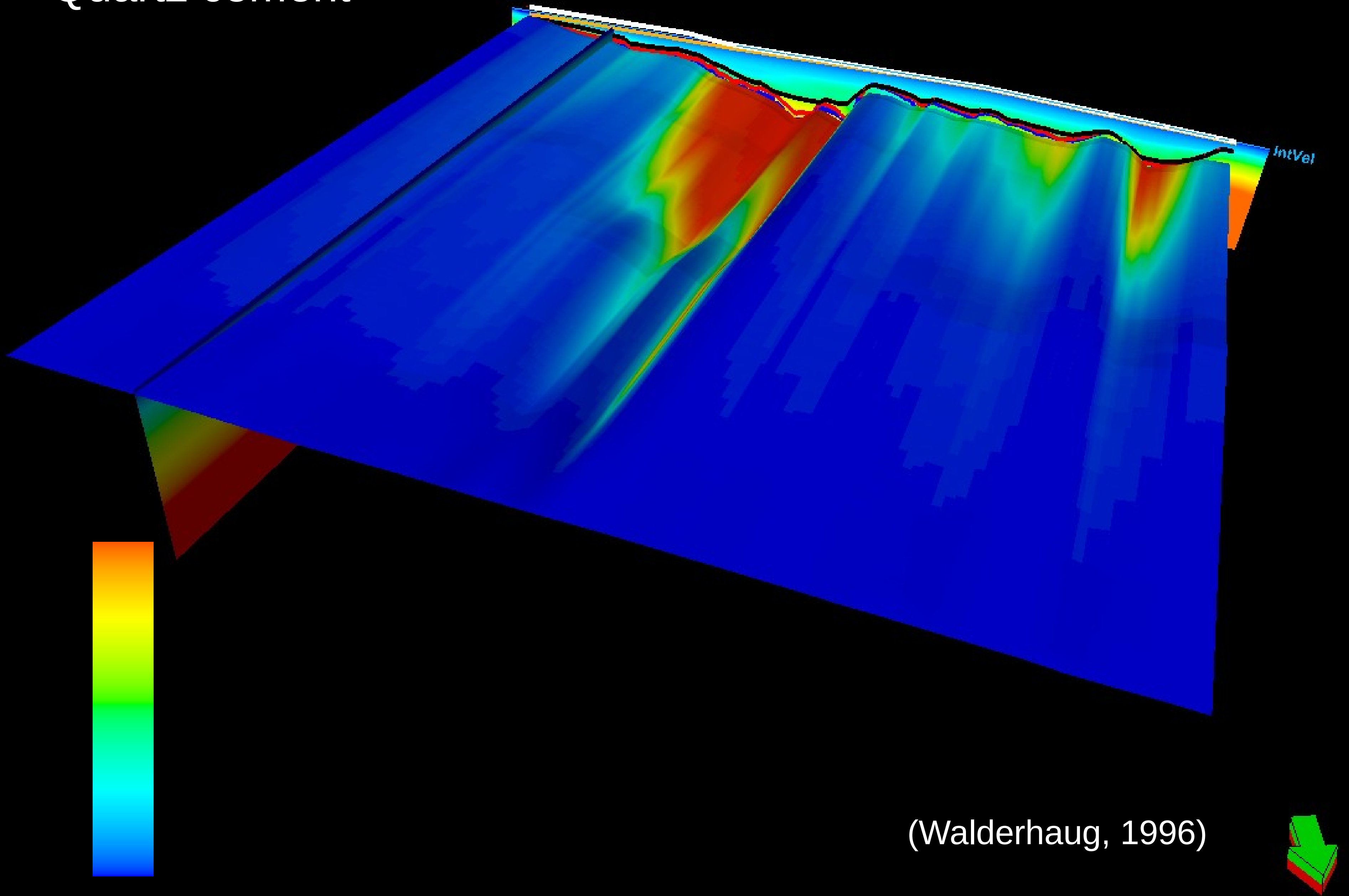


Priyanto, Hokstad, Zwach, V Shaack, Mjøs, Hartadi, Duffaut, Tasarova (2015): **Heat Flow Estimation from BSR: An Example from the Aru Region, Offshore West Papua**, Indonesian Petroleum Association, Proceedings

Top Brent Temperature

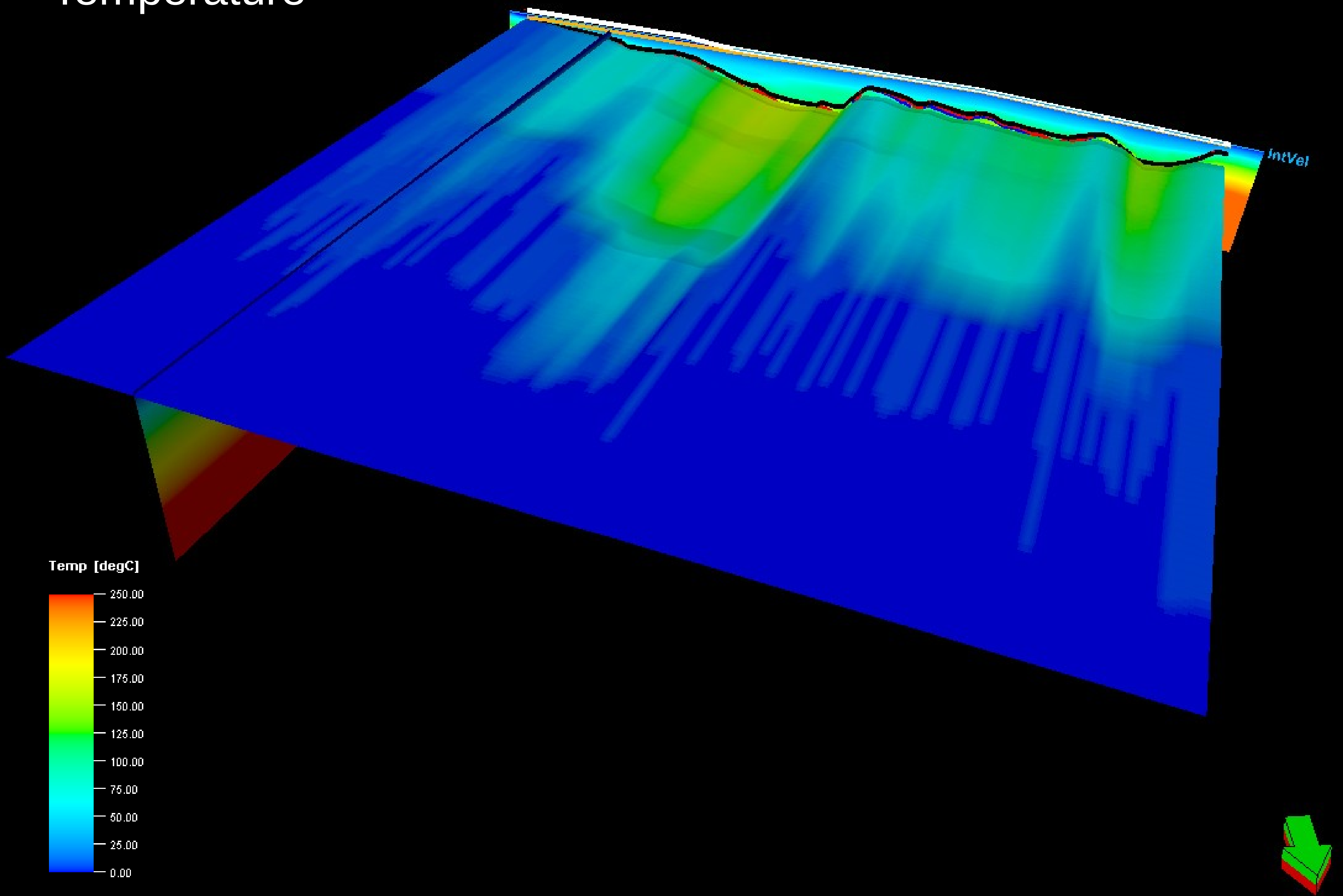


Top Brent
Quartz cement

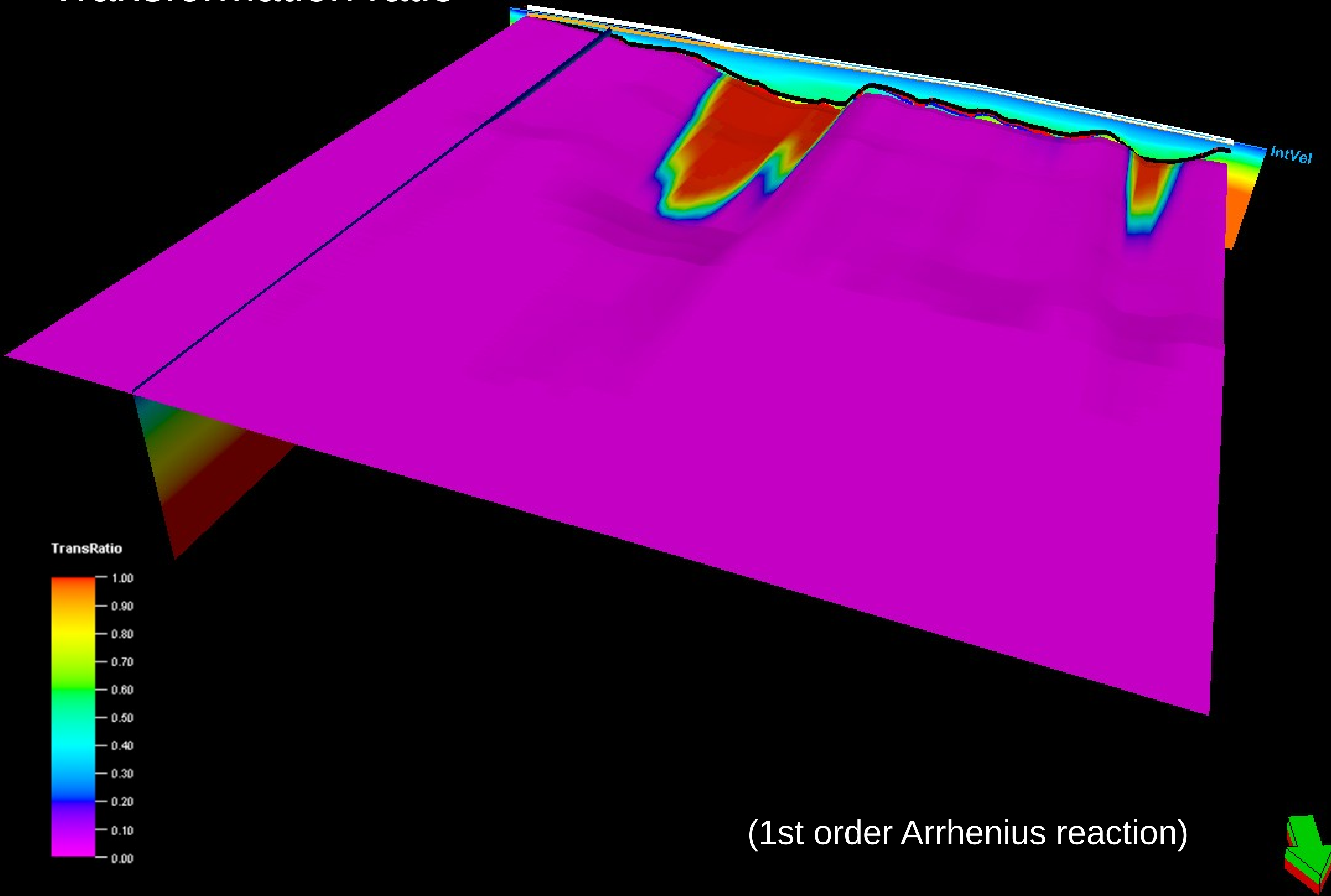


(Walderhaug, 1996)

BCU
Temperature



BCU
Transformation ratio



(1st order Arrhenius reaction)

Conclusions

- New appraoch to thermal modeling
  - Based on geophysical data and rock physics model
  - Objectives and application similar to conventional basin modeling
- Demonstrated on Viking Graben (Line NSDP-84-1)
- Tested with good results in different settings, inside and outside Norway
  - Continental shelf (Barents Sea, North Sea)
  - Passive margin (Norwegian Sea, West Africa, East Africa)
  - Subduction zone (Sea of Okhotsk, Indonesia)
  - Onshore (Ural-Volga)

Acknowledgements

We thank

- Ketil Kåsli for initiating our research on thermal modeling
- Kjell Inge Skjønberg for turning our research Matlab codes into Petrel plugins
- Anders Dræge, Jan Ove Hansen, Kristin Rønning, Torbjørn Dahlgren, Luppo W. Kuilman, Bagus Priyanto, Michael Erdmann, Stoney Clarke, Lill-Tove W, Sigernes and Olav K. Leirfall for discussions
- Statoil for permission to publish this work