IES GmbH

Petroleum system modelling

Made 100% with Open Office!

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PSM - Outline

Day 1

- Petroleum system
- Heat; measuring heatflow
- Time
- Traps
- Modelling 1D, first play

Day2

- Problems: salt
- Modelling
- 1D is powerful!
- Playing with 1D models

PSM – Outline for today

- Why and what
- PS, reservoir, seal, source rock
- Heat
- Alchem...oops, Geochemistry + heat
- Time
- Trap, seal
- Modelling
- Seismic stratigraphy
- Play with a 1D model

Why and what?

Oil & gas in a reservoir? Then all 5 items of the Petroleum System worked correctly, now and in the past

We make a model to integrate and understand all the Petroleum System info

How to sell this work to accountants/management?

REDUCE RISK!

What is a petroleum system?

1. Reservoir
2. Seal
3. Mature Source Rock
4. Trap
5. Timing of migration

Theirs....

What is a petroleum system?

1. Mature Source Rock
2. Migration
3. Reservoir
4. Seal
5. Trap
6. Timing

“I did it my way....”

PS: source rock

A rock layer that produces oil on heating

Shale, carbonate with organic matter (kerogen)
(can be sand with dispersed resinite or alginite....)

Can cover a large area and may be a seal

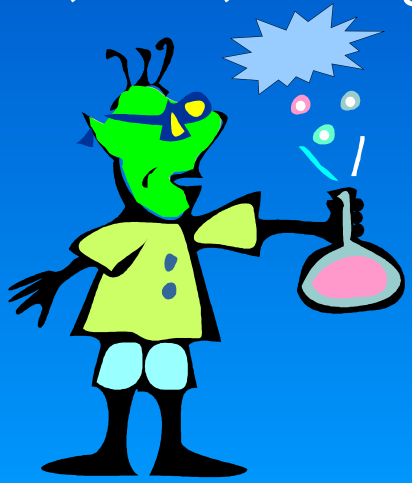
Alert:
source rocks are ↔ and ↕ not homogeneous!

PS: source rock

Appearance

Easy: Black, fine grained, laminated, greasy, smelly
Difficult: Brown or white, fine grained, laminated, (smelly)
Mean: Dispersed

Found by: Looking at rocks, core, cuttings; log cross plots, Rock Eval



Organic Matter

in sediment, requires:

Production (4 billion years)

land: plants (wax, lipin)

water: plankton, algae (cell walls); 90% of biomass

Preservation

Anoxic sediment and water

Covered by sediment (but not diluted!)

- Burial and diagenesis causes polymerisation
- OM $\rightarrow$ **Kerogen**

Kerogen analysis

Rock Eval, as in experiment

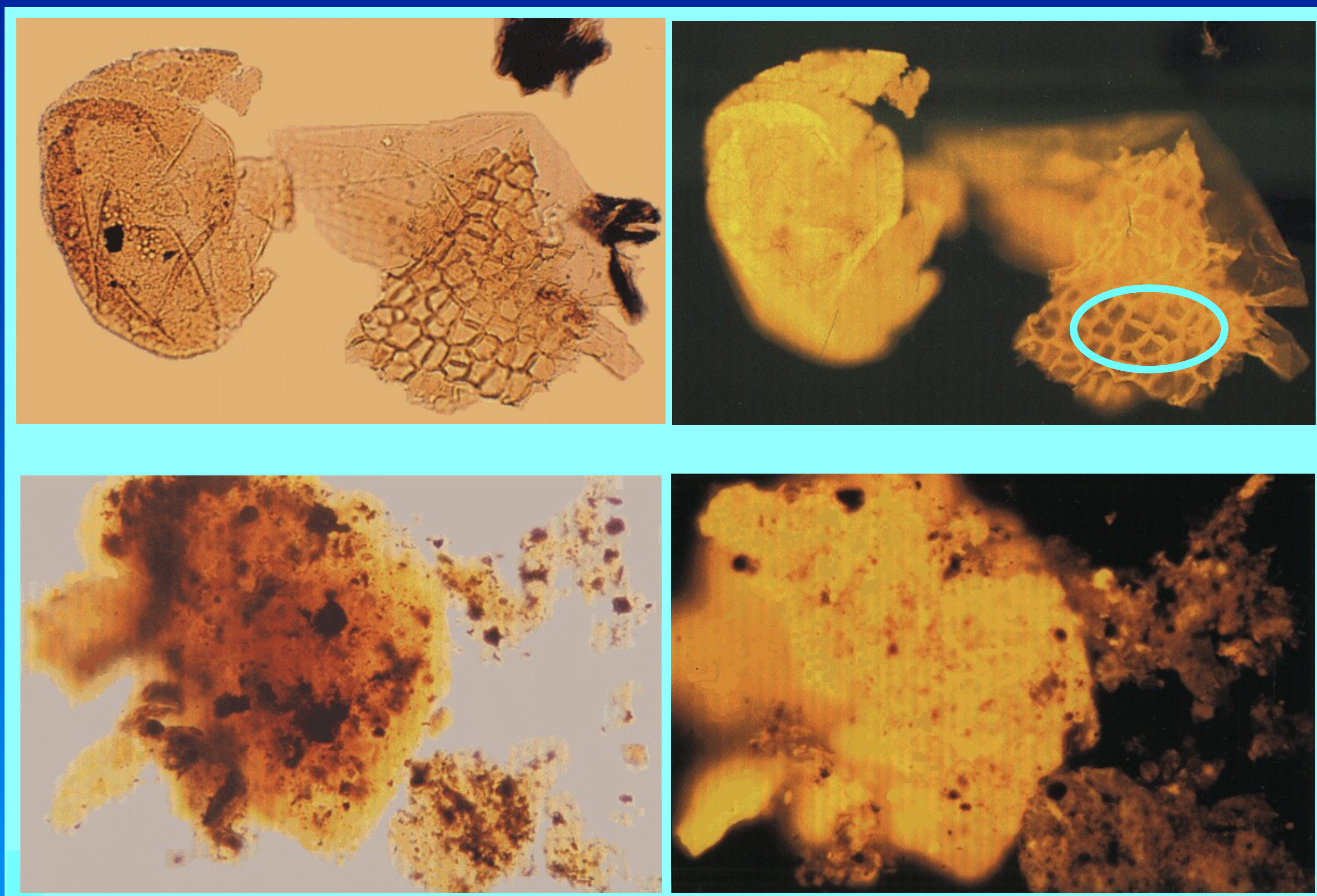
measures how good, how mature and what type

Vitrinite reflectance, Ro (is coaly material in rock)

how mature and what type, much more precisely

Kerogen

White light UV light

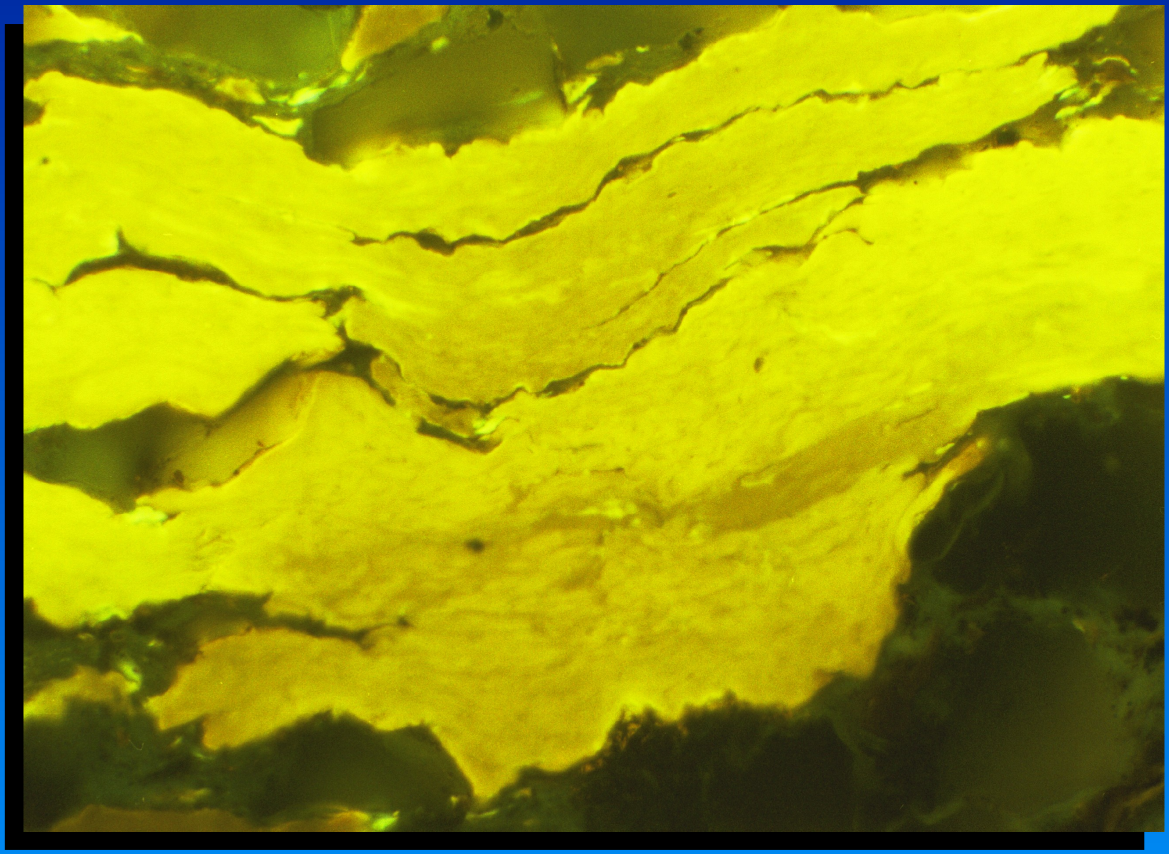


Spores, cells

Amorphous

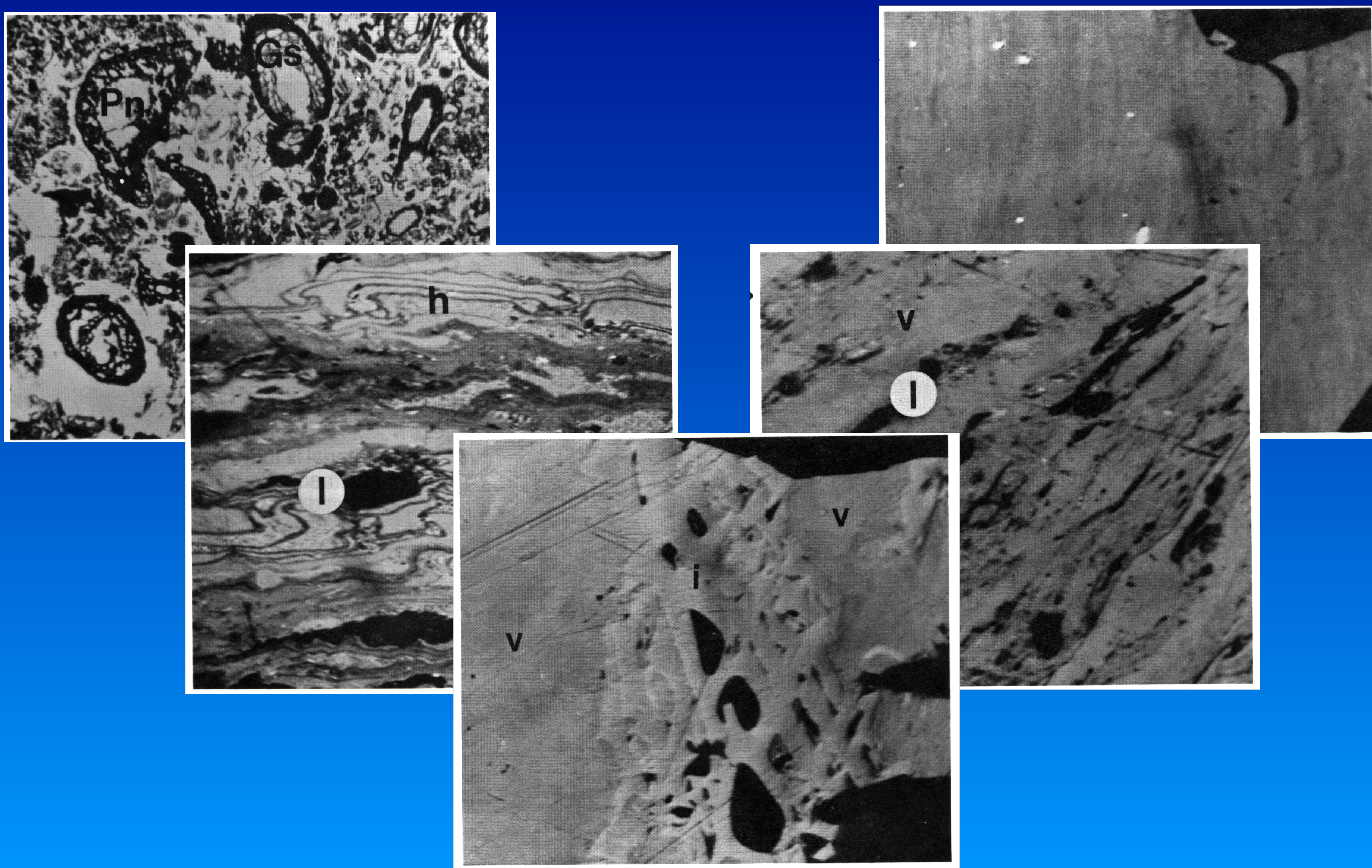
*from:*Hunt, 1996

Kerogen, algal

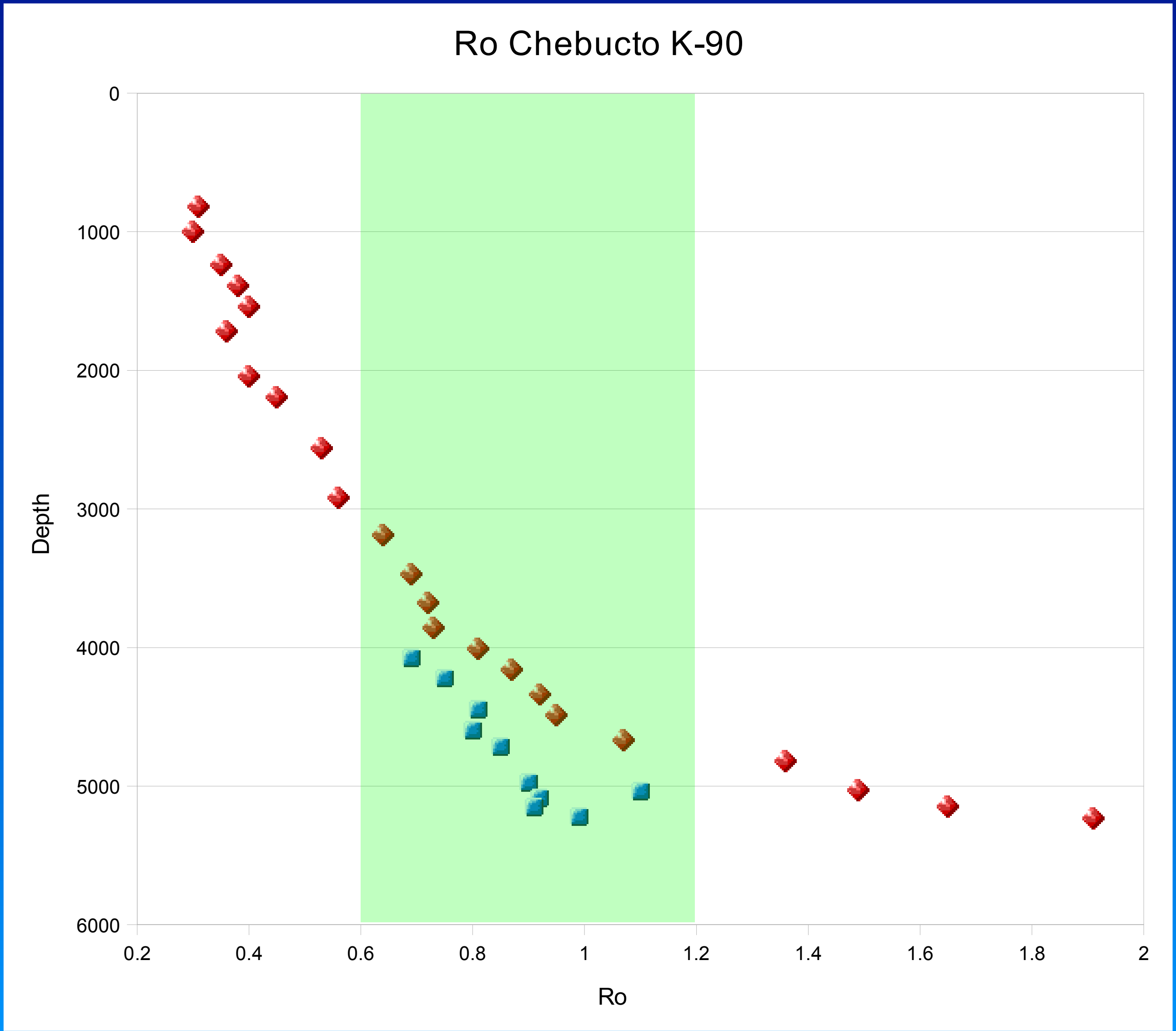


500 Ma alginite, NWT

Vitrinite



Vitrinite


Ro Chebucto K-90
Depth
Ro
0
1000
2000
3000
4000
5000
6000
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Source Rocks

(Fine grained rocks with enough kerogen to generate hydrocarbons)

Organic Matter:

Type	Source	Environment	Produces
Type I	Algal	Lacustrine / Marine	Oil
Type II	Dispersed sapropelic	Marine	Oil & Gas
Type III	Coaly	Terrestrial	Gas

Type IV.....

Principle of Burial: heat flow

Warmer with depth....

Heat comes from mantle, core, and originally radioactive decay

Crust is the conduit.

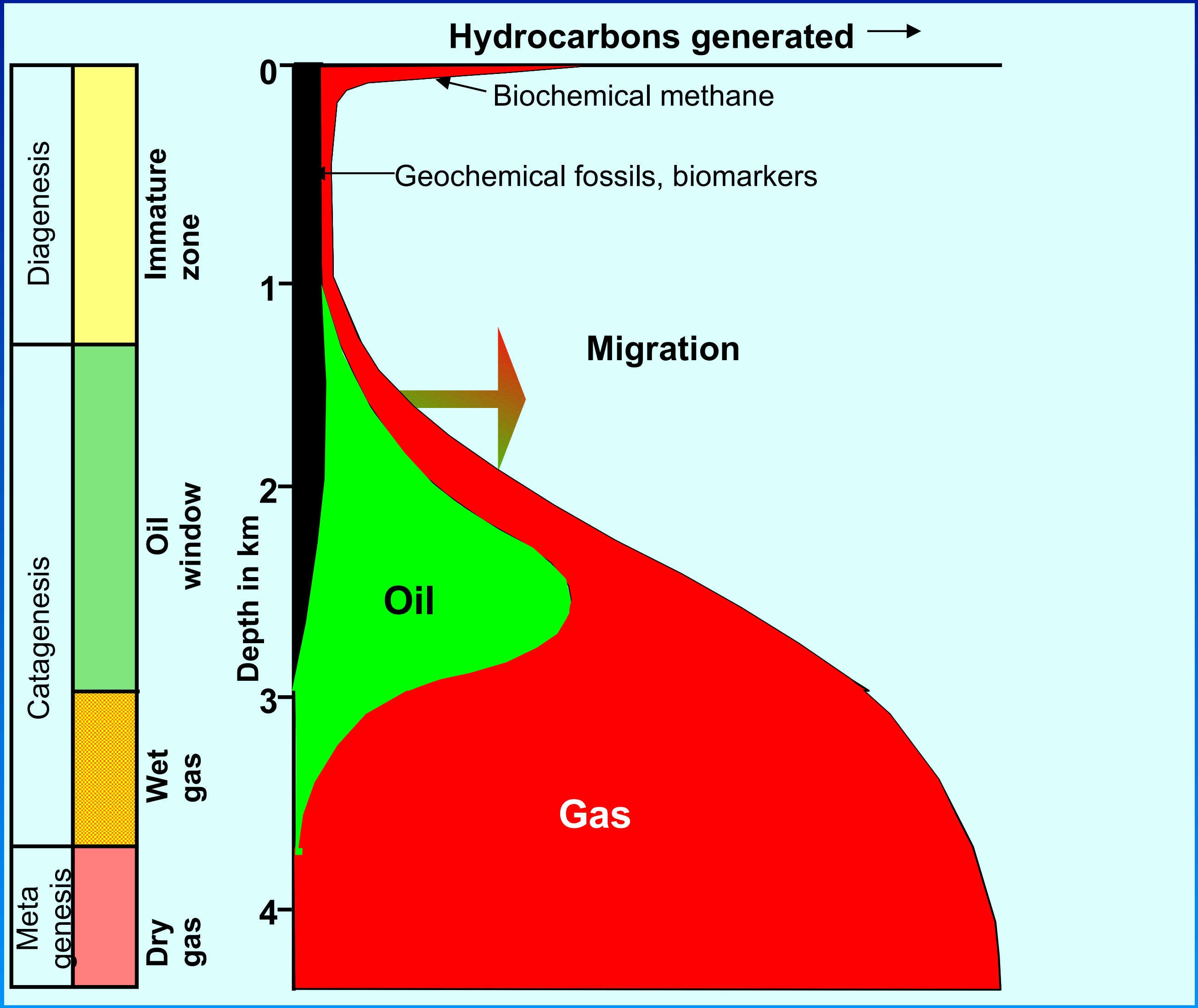
Geothermal gradient is far too coarse.

Measure with

- thermometer
- heat flow probe ***Keith Louden....***
- vitrinite, fluid inclusions, FTA ***Marcos Zentilli....***

Heatflow is the most sensitive factor in the PS!

Hydrocarbon Formation



After: Tissot & Welte, 1984

Gas generation

Bacterial (shallow)
Cracking (deep burial)

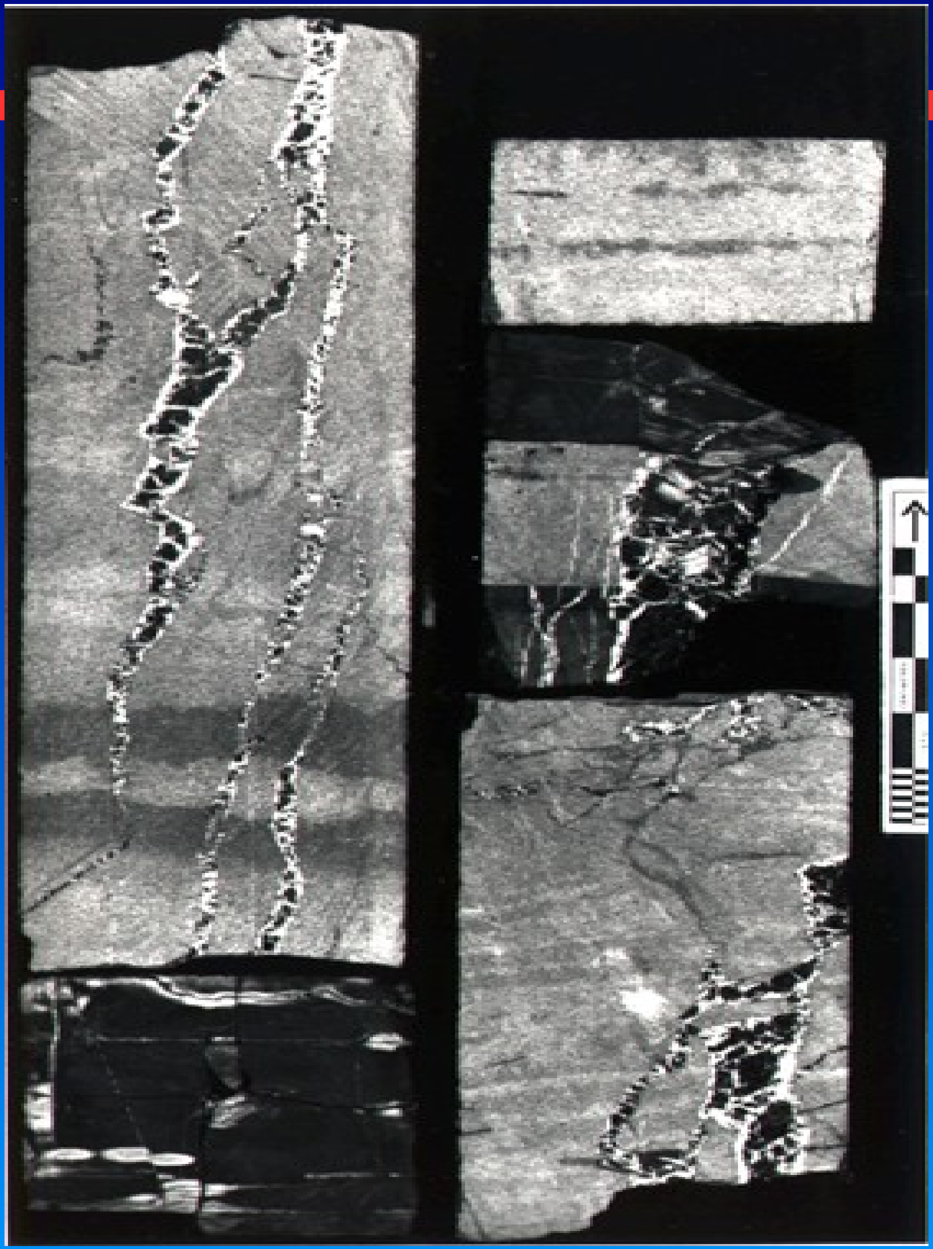
Source Rocks

Maturation

- Burial increases rock temperature
- 85^o to 120^{o}C: generation of hydrocarbons
- Volume increase fractures the rock to release pressure
- HC moves out, up or down:

Primary Migration or expulsion

E
X
P
U
L
S
I
O
N



H
y
d
r
o
f
r
a
c

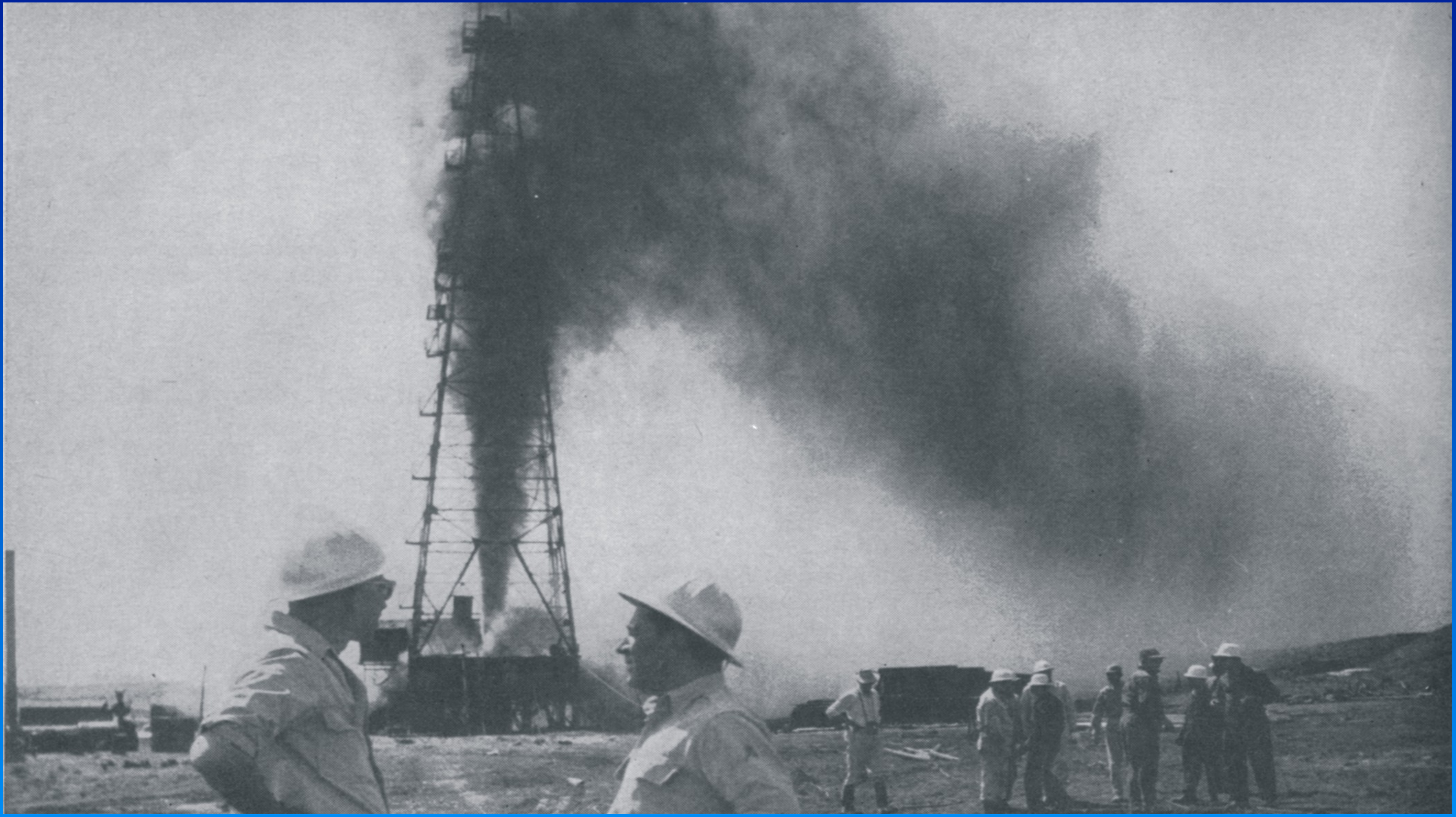
Hydraulic fracturing

Needs:

- A good seal
- Volume increase from kerogen breaking apart, or/and
- Mineral reactions from diagenesis

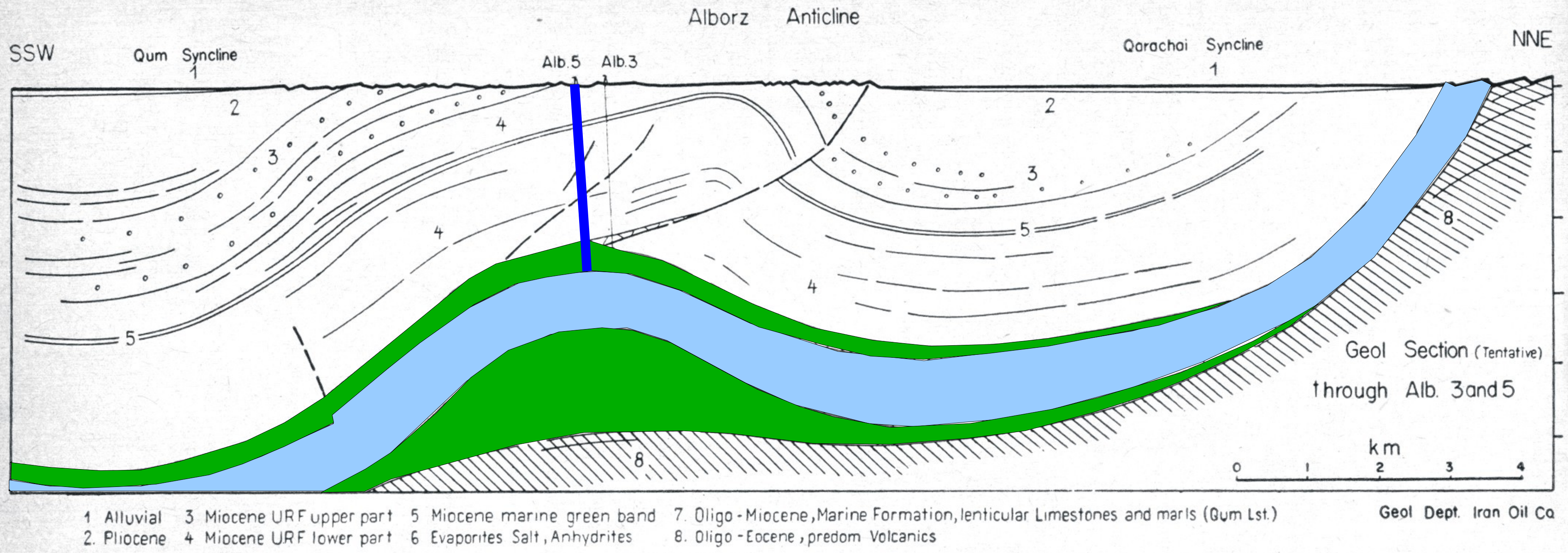
Example: ***Alborz blowout***

Alborz 5



Alborz 5

Alborz 5



WELLS 3 and 5, drilled about 5 km. west of wells 1, 2, and 4. (Fig. 4) confirmed the extent of the large structure. Well 5 consumed 6 months in penetrating the evaporite section. When it tapped the limestone, pressure blew 17.2 lb. per gallon mud from the hole. Fig. 5.

Alborz 5, what happened?

- 1934 seep.
- 1944 geological survey by Dutch company: no oil possible!
- 1950 geological survey by Nat Iran Oil Co: Anticline 50 x 12 km. Target is Qum limestone that outcrops. No seismic
- 1951 Oil seep in gypsum near limestone outcrop. Test wells:
  - Alborz 1 confirms sediment Produced some OGW from 1545 m at 1.4 Mpa. No logs
  - Alborz 2 to confirm structure and thrust. Oil stained sand, DST nothing
  - Alborz 3 in 1953 finds unexpected salt at 2130 m, and drilling problems start. 4 mths to drill 100m; at 2300 m inflow at 34 Mpa; at 2325m oil & gas inflow; DST dies. Waxing of oil at P drop?? Continue drilling, liner bends. Why? Stuck, end of rig capability. SI 10 Mpa; flowed oil then 13 MPA.
- 1954 Cored 800 m limestone!
  - Alborz 4 Close to crest. Reaches salt, stuck. Skid, drill 4a, stuck
- 1955 Seismic confirms Alborz 3 as best location, redrill 500 m south as Alborz 5. Fieldwork: limestone is variable laterally, irregular permeability.

Alborz 5 in 1956. Set casing at top salt (on target). Is salt + anhydrite + clay. After 30 m stuck. Recover, next day stuck again. Sidetrack after 1.5 months. 200 m deeper, stuck. Sidetrack. At 2600 m Globigerina: near limestone. Expect fractured limestone and loss of circulation, reduced mud weight slightly. At 2700 m change in rock: chalky anhydrite. Then 0.5 m deeper “hard rock”. Drill 5 cm into it, at 3.30 h at night on 26 August. Mud blew out. BOP closed, but packers torn out. Cut electricity, left (dark). At daylight: oil 30m over crown block, sprayed gas and oil kms around. No fire. Dams put up. 80 000 bpd measured, not counting lost spray and gas. Capped well, but could not shut in, P too high for casing and head. Partly closed, P= 31MPa. Problem: sediment: abrasion in equipment. Special equipment from US fails as soon as mounted. No valve available for this P, and T of 115^{o} C.
New well head. Choked to 17 Mpa, reduces sediment. Nov 16 while changing lines, well caves and bridges itself between casing and drill pipe. Produced 5 million bls, 3 oil lakes. Blew 82 days. Not yet reopened or drilled.

Under the salt, pieces of limestone likely float in fluid, hence super permeability (5 cm in! with casing 23 cm). No gas cap, all gas dissolved into oil.

If drilled today, likely again blown out!

Migration

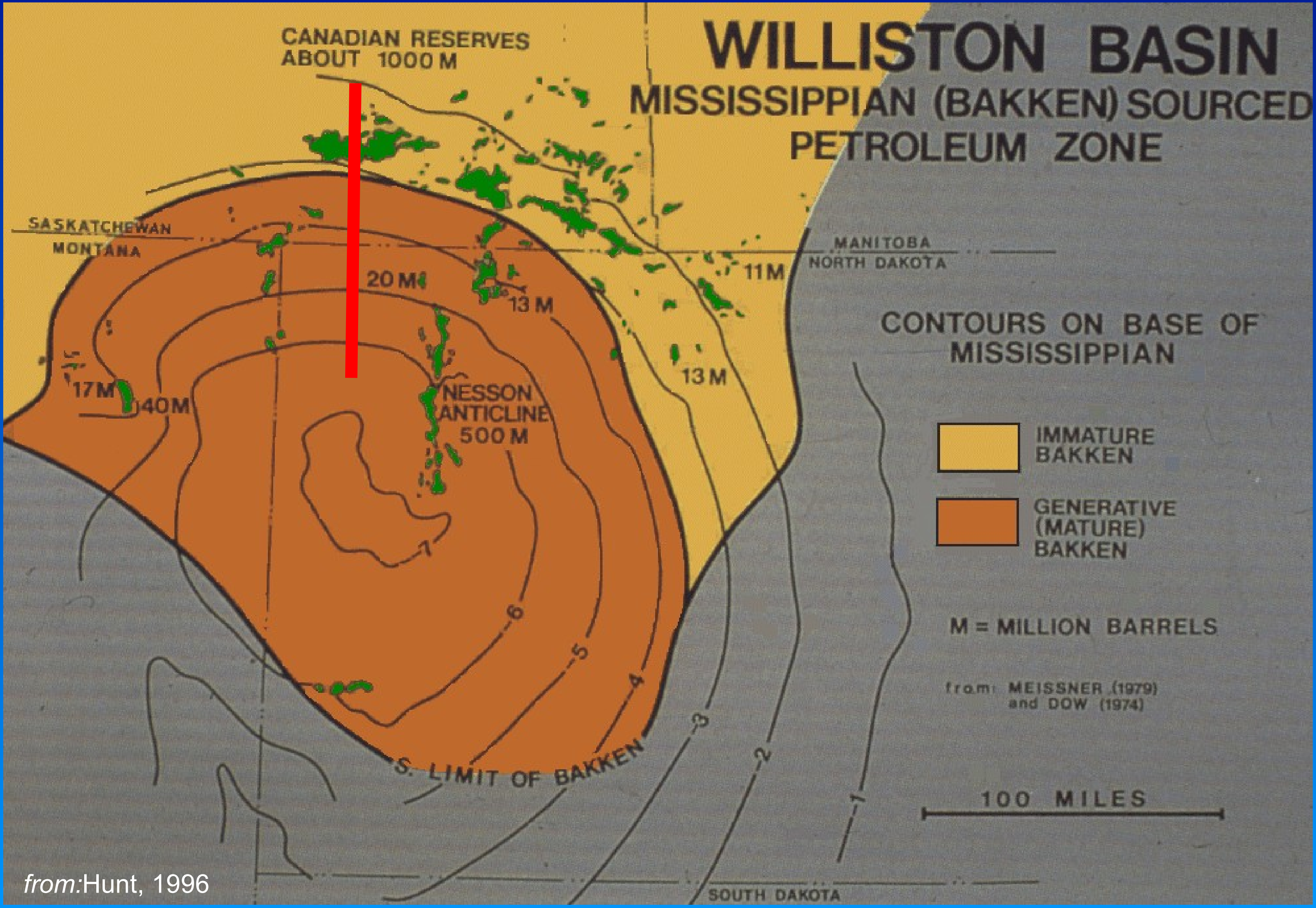
=Movement of HC to trap (hopefully)

HC in porous beds = H_2O + HC + CH_4 (+ rock)

Force =	BUOYANCY
Speed:	Now how fast does this go?
Direction:	Steepest way possible UP
Stops:	At seals: coagulates
	No seal: to surface (seep)
Distance:	0 - 100's km
Re-moves:	If basin tilts in other direction

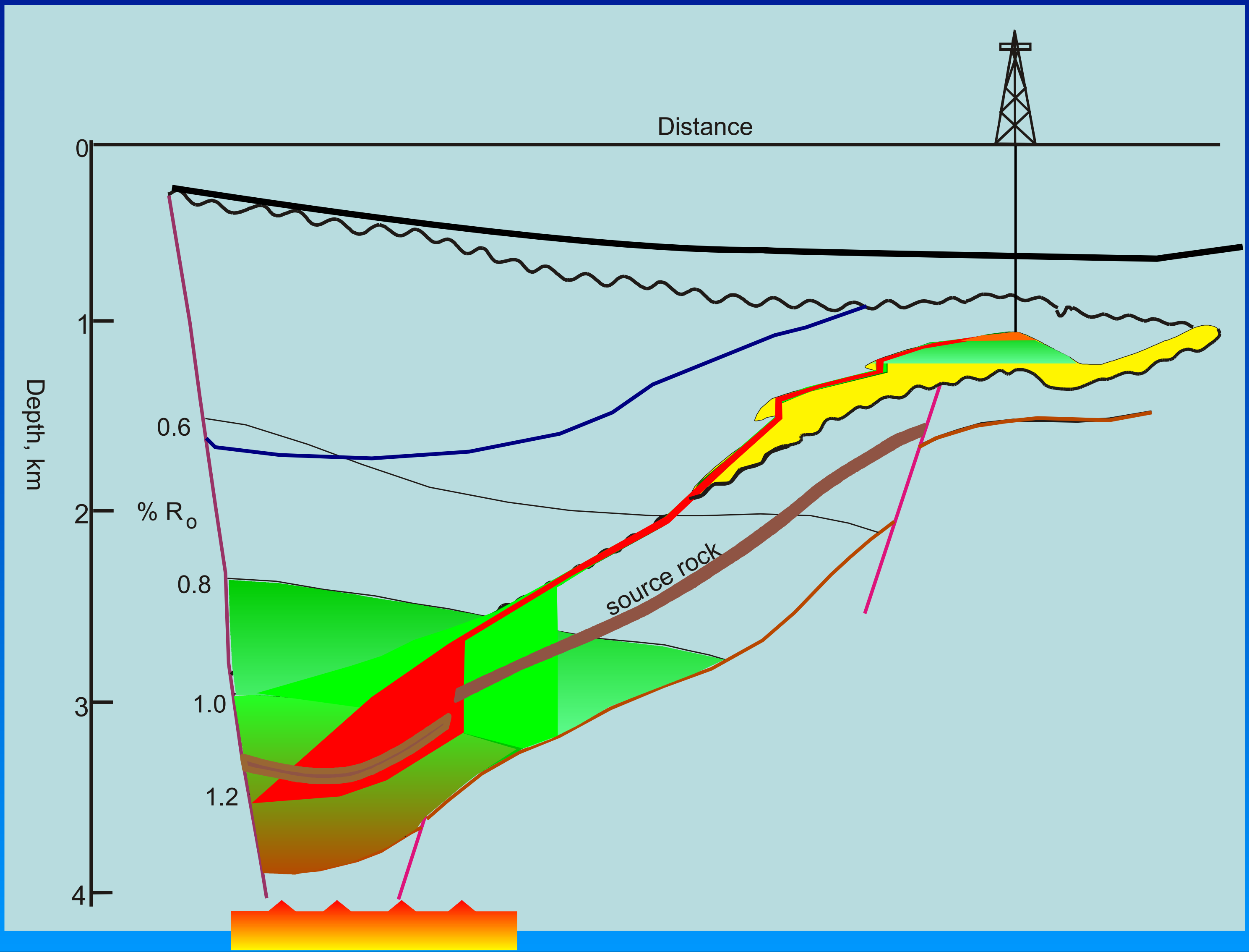
Evidence of migration: Staining along seals

Example



WILLISTON BASIN
MISSISSIPPIAN (BAKKEN) SOURCED
PETROLEUM ZONE
CANADIAN RESERVES
ABOUT 1000 M
SASKATCHEWAN
MONTANA
MANITOBA
NORTH DAKOTA
SOUTH DAKOTA
20 M
13 M
11 M
13 M
17 M
40 M
NESSON
ANTICLINE
500 M
S. LIMIT OF BAKKEN
7
6
5
4
3
2
1
CONTOURS ON BASE OF
MISSISSIPPIAN
IMMATURE
BAKKEN
GENERATIVE
(MATURE)
BAKKEN
M = MILLION BARRELS
from: MEISSNER (1979)
and DOW (1974)
100 MILES
*from:*Hunt, 1996

Migration



Time...

Are the oil expulsion and trap formation correct order?

*(and this order **is** the wrong one!)*

Time of generation is deduced from modelling

Time of trap formation from:

- seismic surfaces
- geology

What is the effect of faults?

WHEN do they open, close, offset?

Trap

Structural

Stratigraphic (no worry about timing)

from seismic surfaces

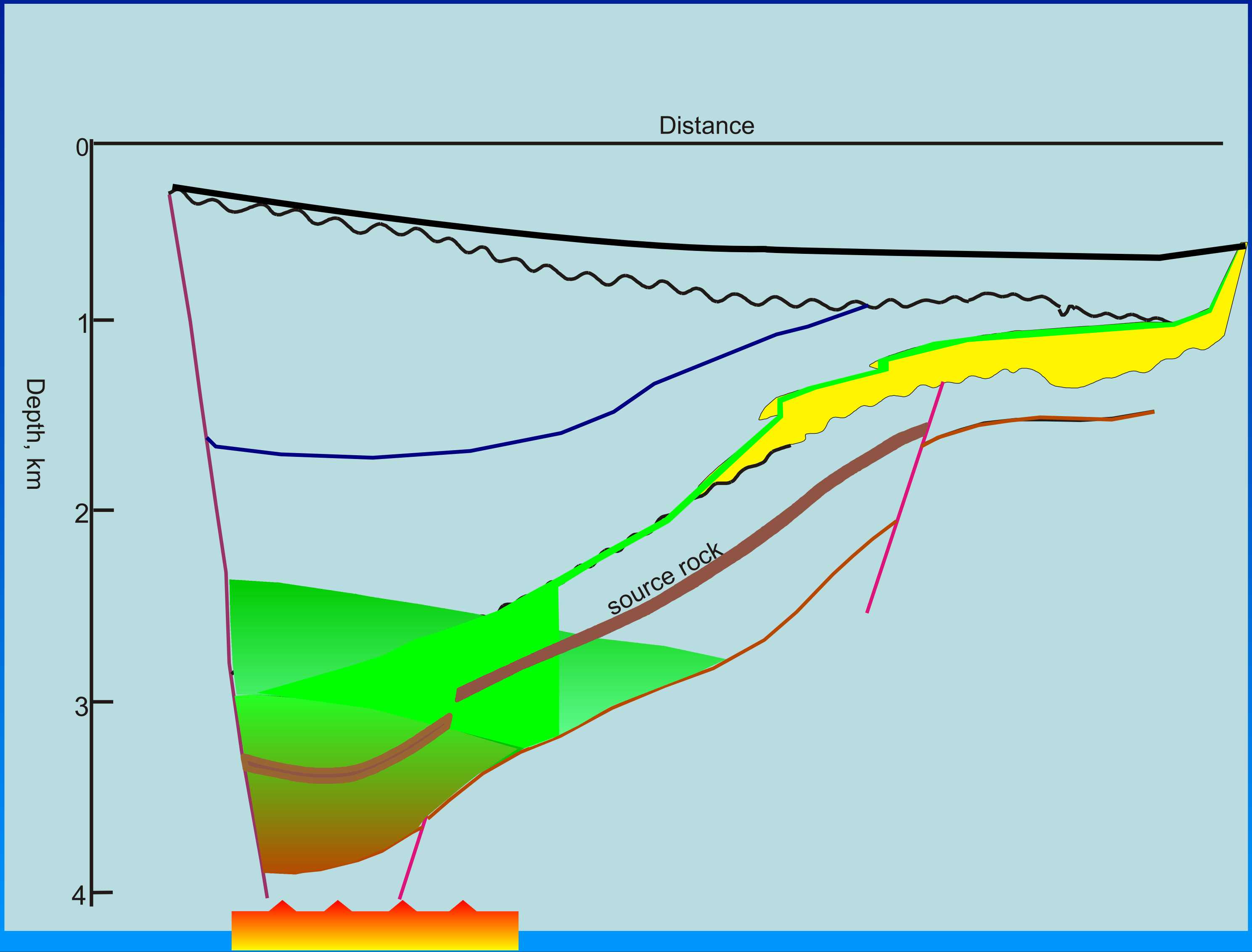
from geology

from analogues

When does the trap form, when does the oil form?

What is the effect of faults?

Timing: trap after oil formed



Trap

Is the earth static?

No!

Later retilt regionally, faulting, folding may destroy a trap

In the “perfect “ trap: biodegradation can happen!

PS: reservoir

A rock layer with *connected* holes
(porosity + permeability!)

- Sandstone, Conglomerate, Limestone, Dolomite
- Also coal, fractured shale, fractured basalt etc.

Alert:
Blanket reservoirs do not exist!
reservoirs are ↔ and ↕ not homogeneous!

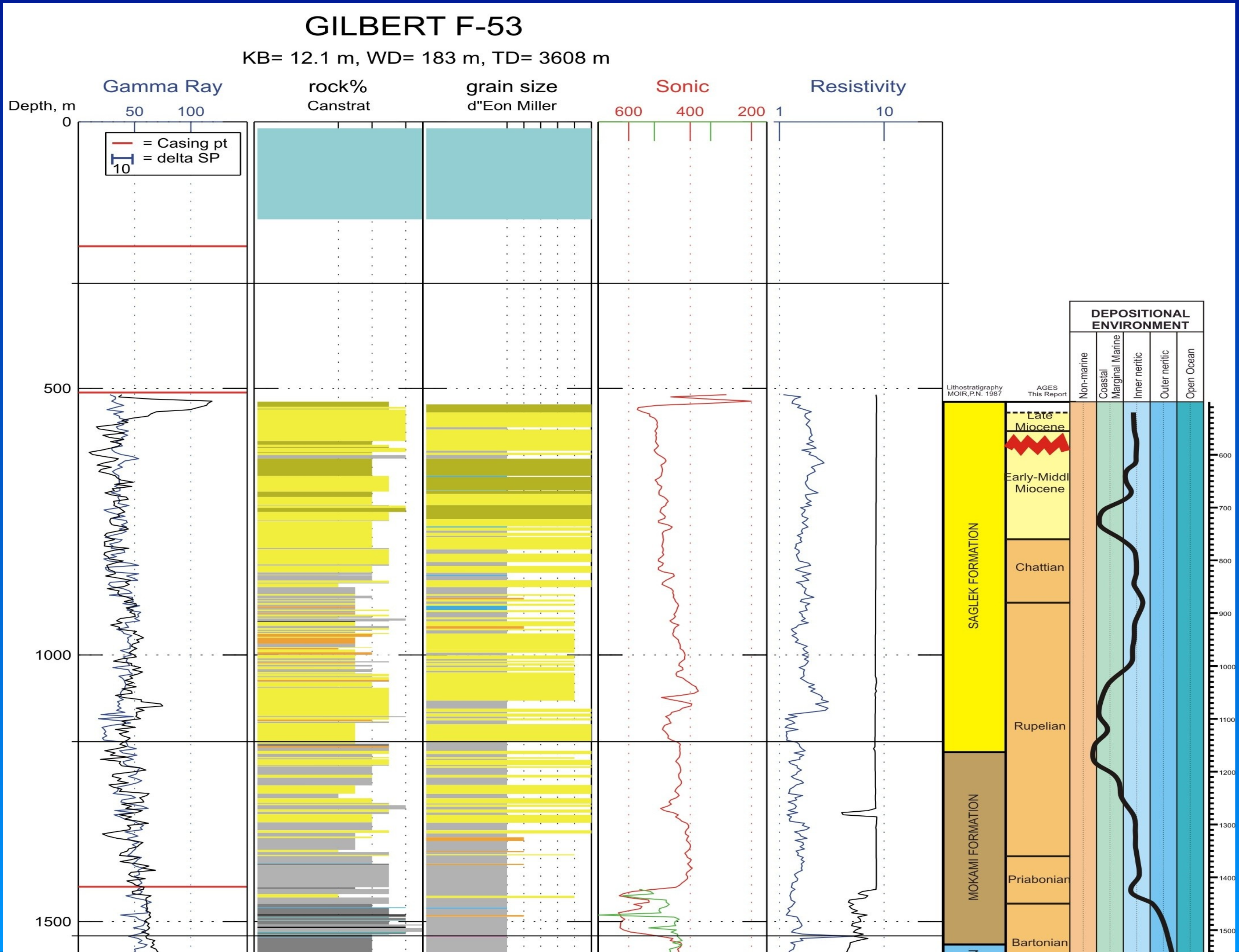
PS: seal

A rock layer like a steel plate

- Shale, salt, gypsum, quartzite
- also tight sandstone, conglomerate, limestone, dolomite basalt etc.

Alert:
Nothing is a perfect seal
Blanket seals do not exist!
seals are ↔ and ↕ not homogeneous!

Age and where to get data



Modelling, where to get data

Integrating our knowledge, 1D - 4D

- ► 1D uses wells; for calibration and nailing gaps
- ► 2D uses seismic lines + preferably wells; for lateral facies
- ► 3D uses seismic surfaces and sequence strat.; for full simulation

►All Ds +1! (time)

Wrap-up

Petroleum system

reservoir

seal

source rock

time-trap-migration

modelling

off to the playpen....

Heat Flow

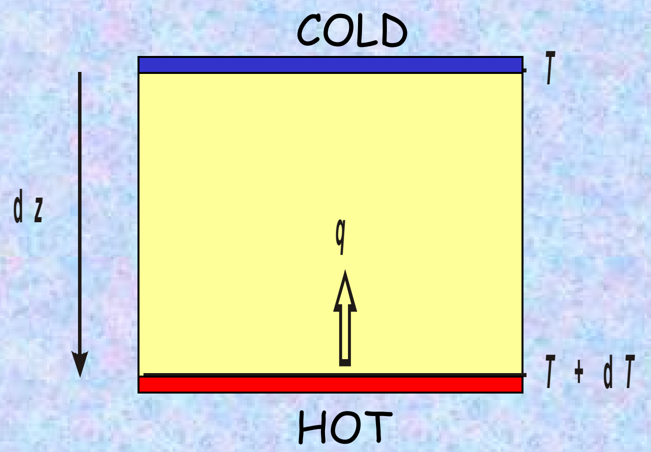
From top to bottom
And hot to cold

Something we have
all experienced
before !

Heat Flow Basics

Definition of 1-D conductive heat flow

For conduction, heat flows from hotter to colder region by transfer of molecular kinetic energy. The material itself remains stationary. This contrast with convection, where heat is transferred by motion of the material. Generally conduction is less efficient than convection.



To Determine the Heat Flow Requires Two Measurements

q	=	k	x	$\delta T/\delta z$
heat flow		thermal conductivity		gradient

Units (MKS)	mW/m²	W/(m-ºC)	ºC/m
typical values			
sediment:		0.5-2.5	0.2-0.02
	50-100		
rock:		1.5-4.5	0.06-0.01

Why Do We Care?

HEAT FLOW is the most fundamental INPUT and OUTPUT of thermal models

How Do We Measure It?

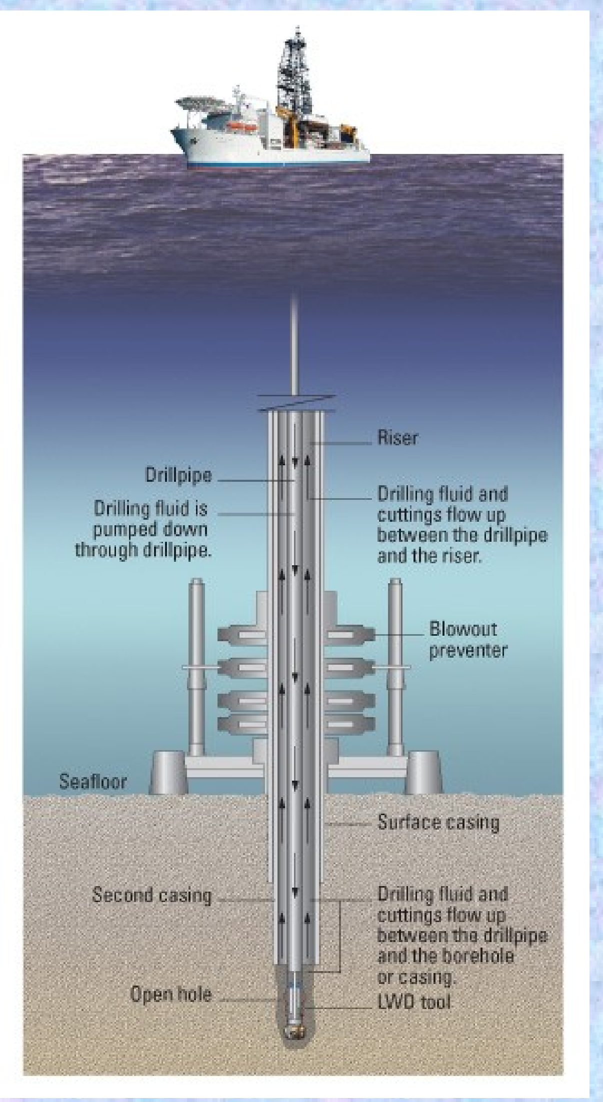
Data from Deep Boreholes and Shallow Probes

The Major Problem?

Disturbance caused by the measurement !

Borehole Measurements

- **Deep penetrations reduce surface effects**
- **Most reliable temperature from drill stem tests (DST) but they are not generally available**
- **Bottom hole temperatures (BHT) taken during interruptions in drilling, but they are disturbed by effects of drilling and mud circulation**
- **Indirect measure of conductivity from logs if no core?**
- **Limited coverage (shallow water)**



BHT corrected using Horner plot method

$$T=VRT+(H/4\pi k)\cdot \ln\{1+(t_c/\Delta t)\}$$

T= temperature

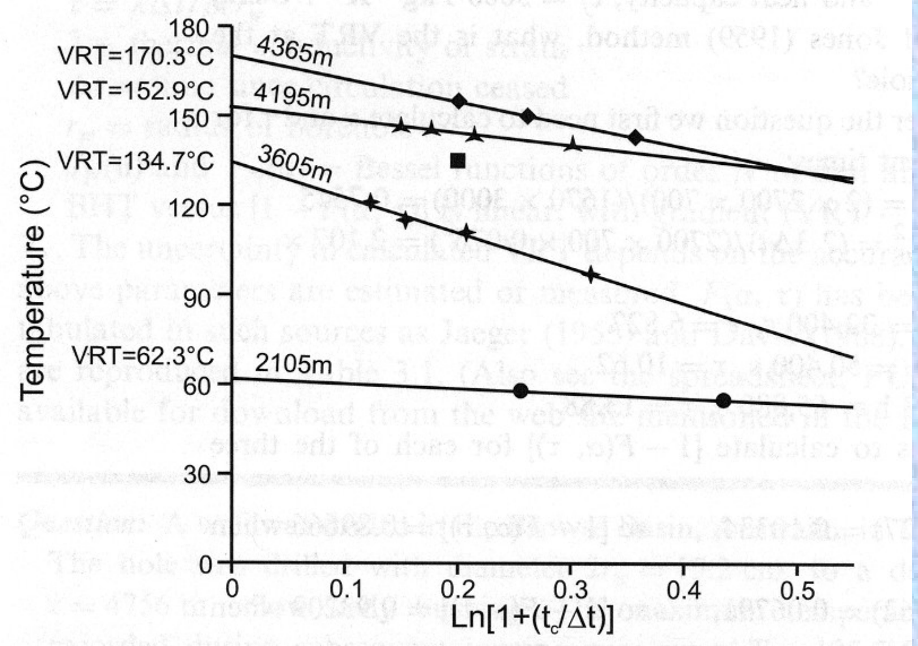
VRT=“virgin rock temperature”

Δt= time from end of fluid circulation

t_c= time between end of drilling and end of fluid circulation

H= rate of heat supplied to well

k= thermal conductivity



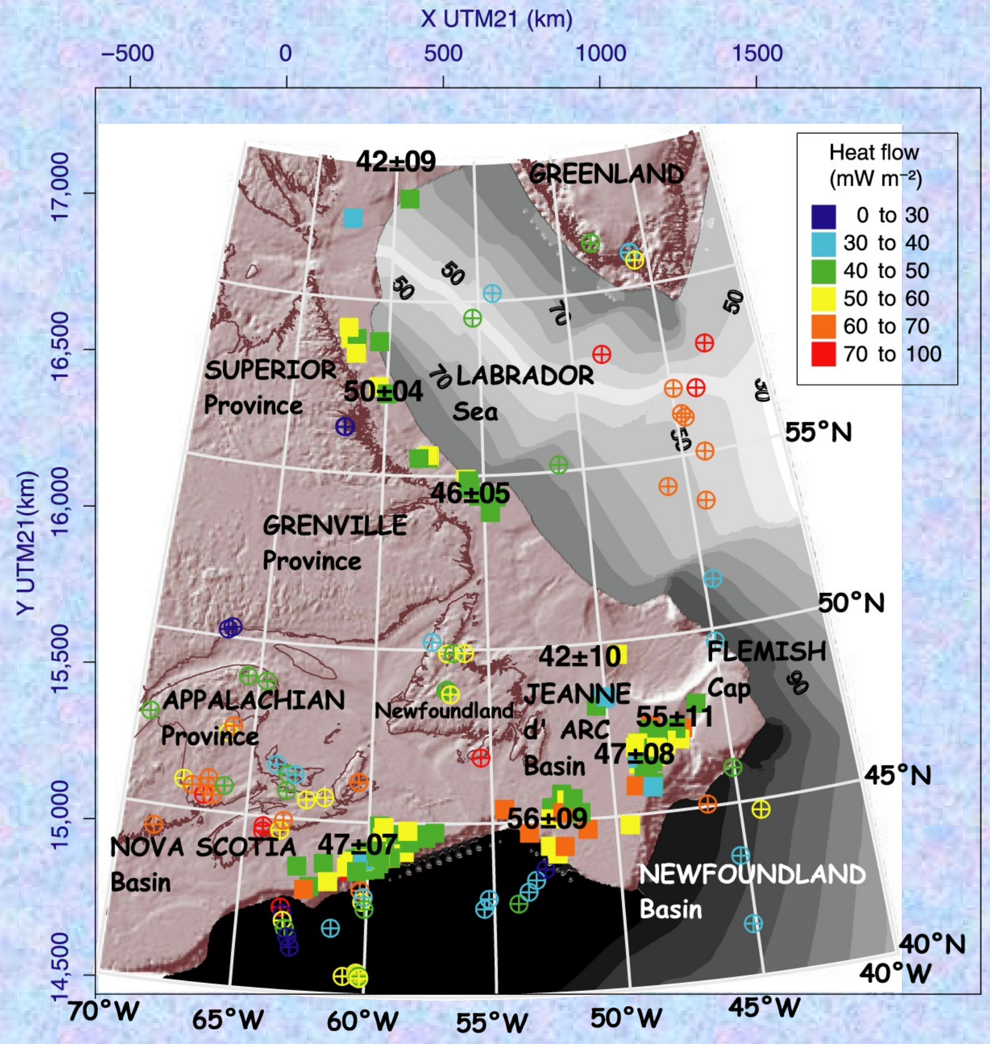
Example Horner plot. Bottom hole temperature data from Browse Basin (western Australia) (from Beardsmore & Cull, 2001. Crustal Heat Flow)

BHT data should only be used as a last resort given the large uncertainties associated with correcting these data. More reliable types of temperature data (i.e., temperature measurements from electronic pressure/temperature gauges used on modern DST/PT equipment from permeable intervals, production log temperature measurements from shut-in production wells) should be sought to constrain the subsurface thermal regime whenever possible.

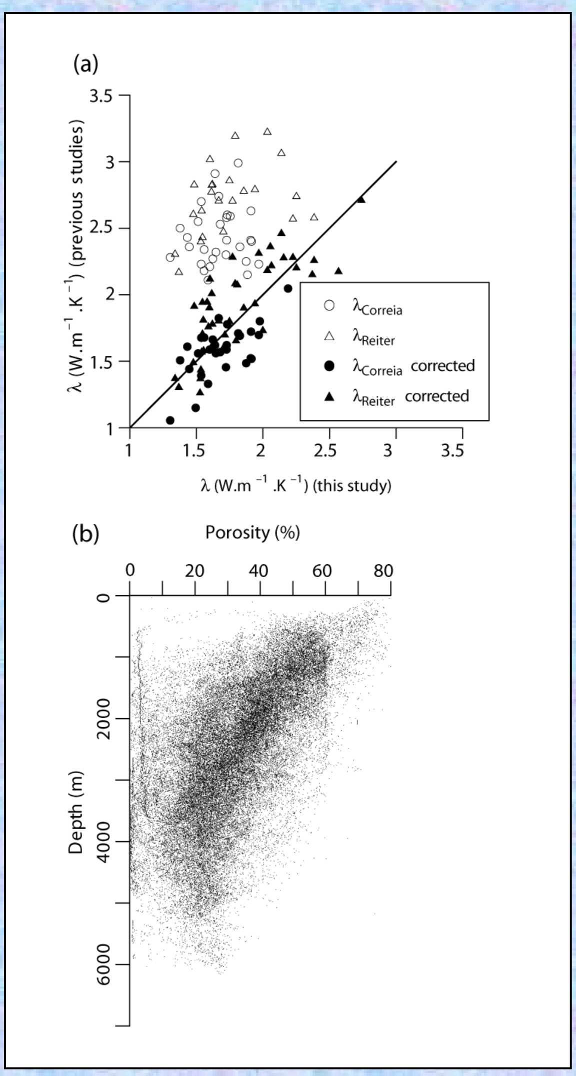
Correcting Bottom Hole Temperature Data
by Jeff Corrigan

Example of Borehole Heat flow Data from Eastern Canada

Conductivity is also important!



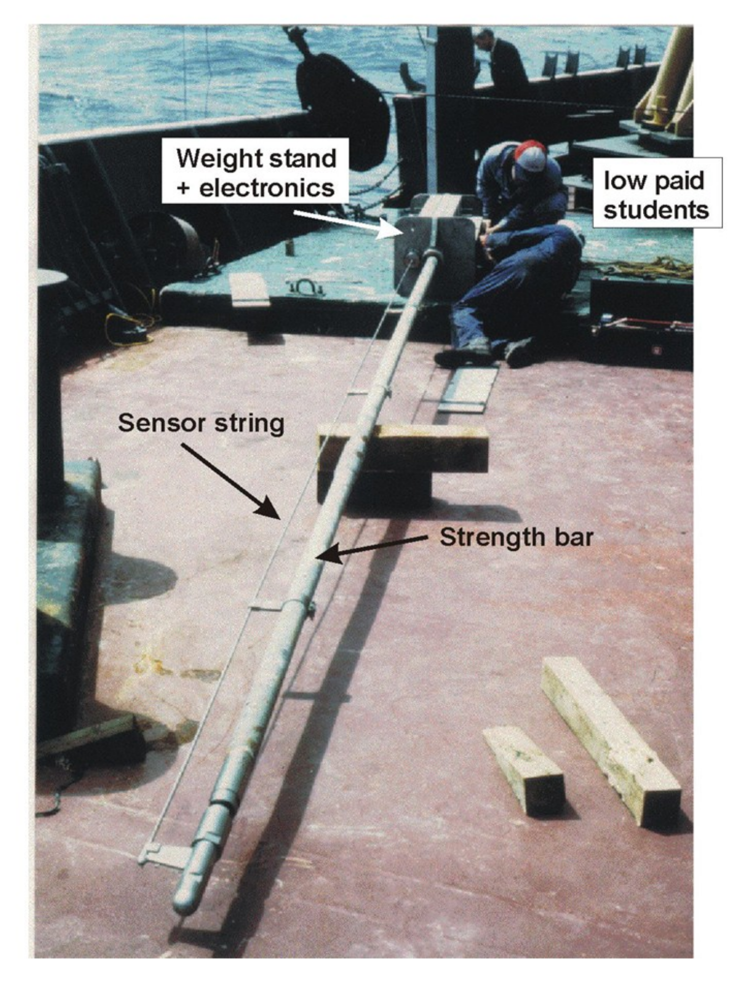
from Goutorbe et al. (2007)



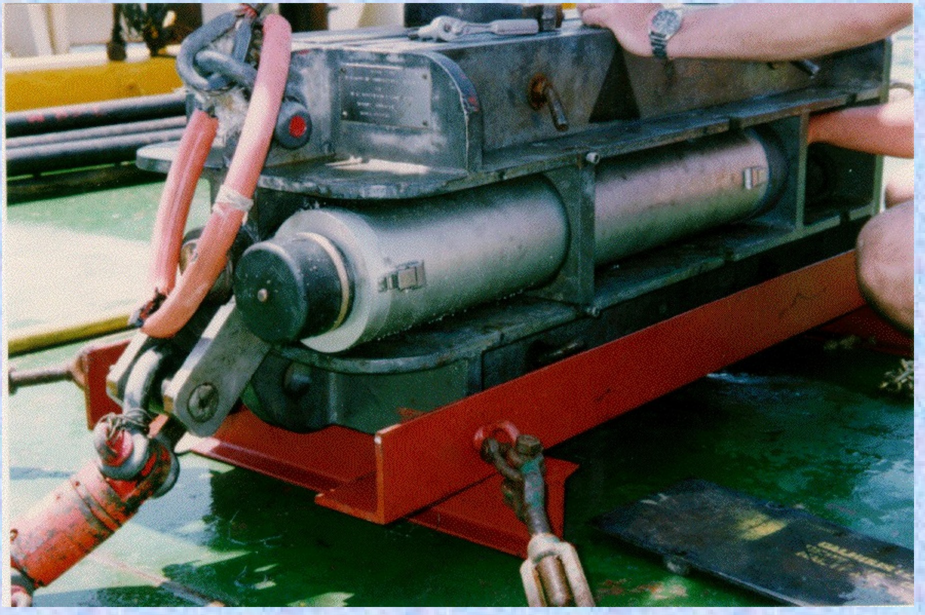
(a) Conductivity corrected for neutron porosity compared to previous values (b) Neutron porosity vs. depth for all boreholes

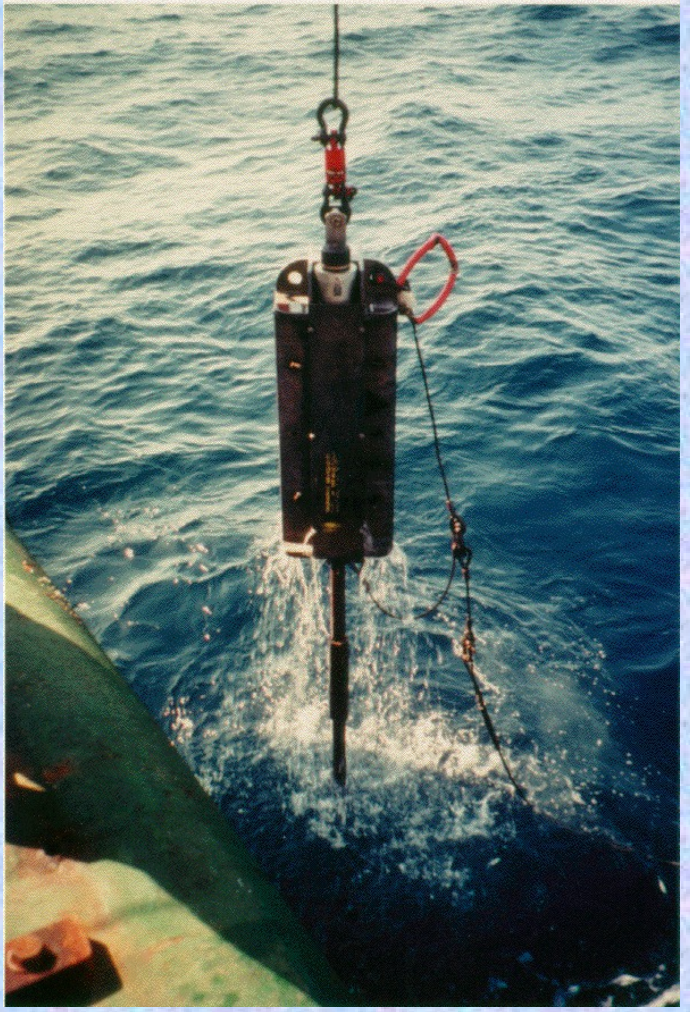
Measurement using Shallow Probes

- Simplified disturbance of sediment
- Accurate and quick measurement of gradient and conductivity
- Possible to take many measurements with wide coverage
- BUT Cannot use in shallow water or hard sediment



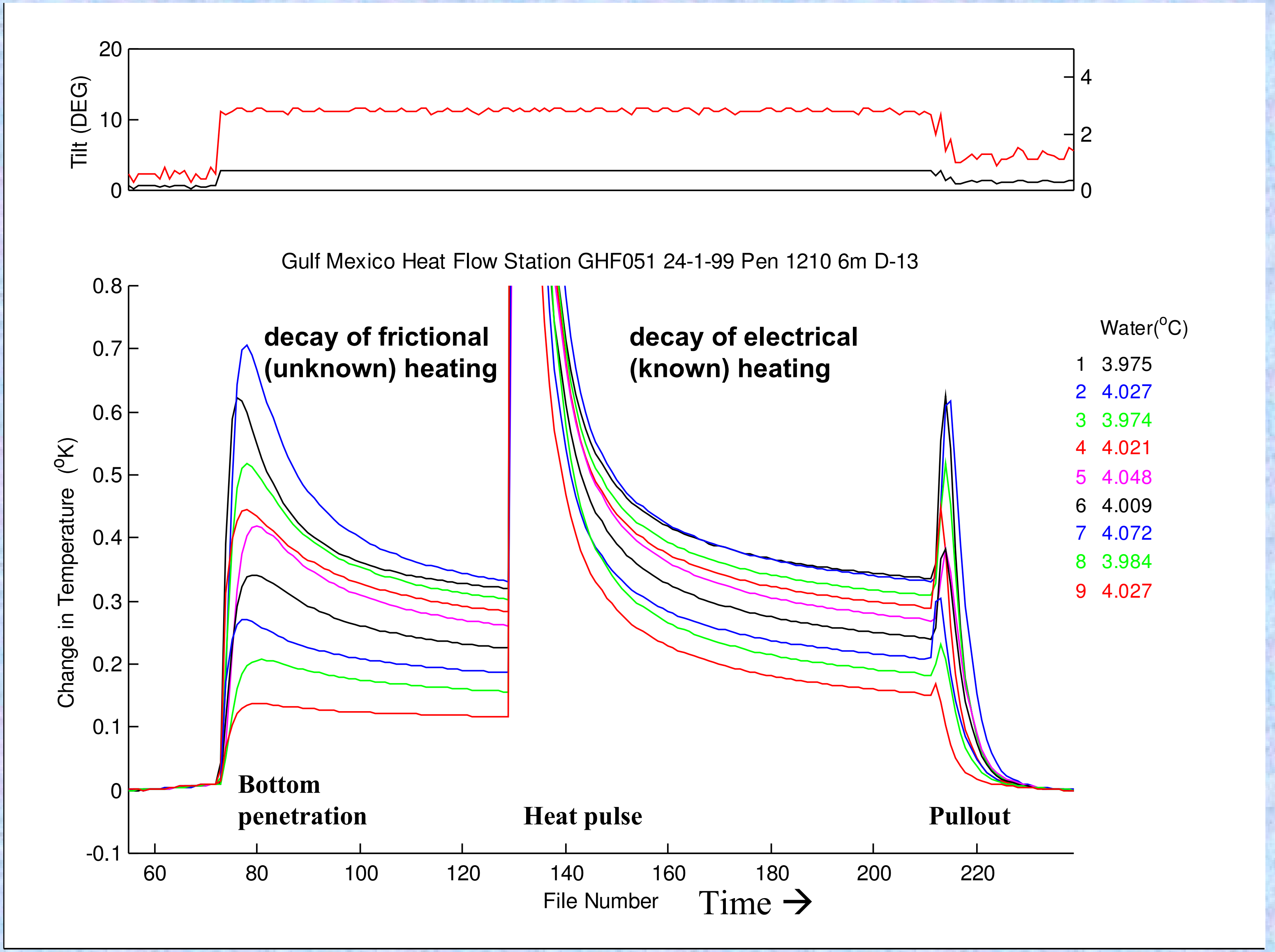
Dalhousie heat flow probe on deck of CCGS HUDSON



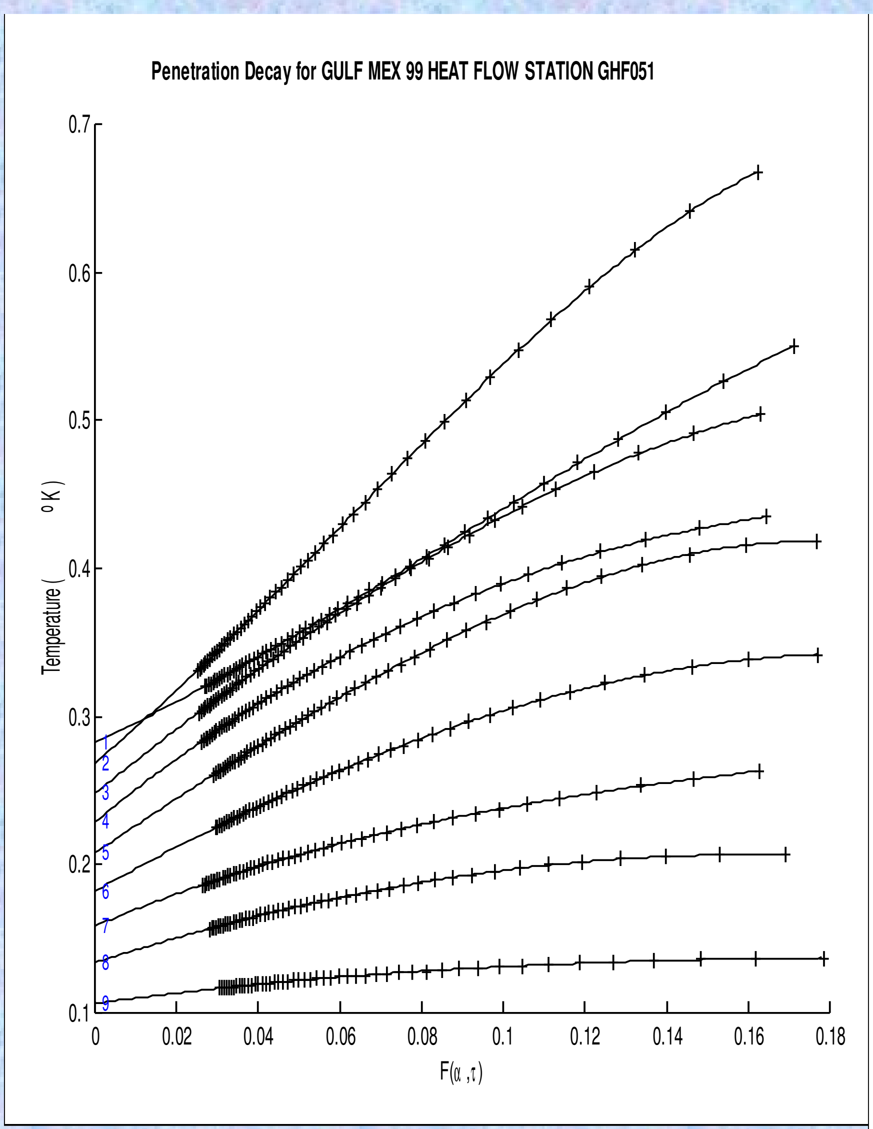


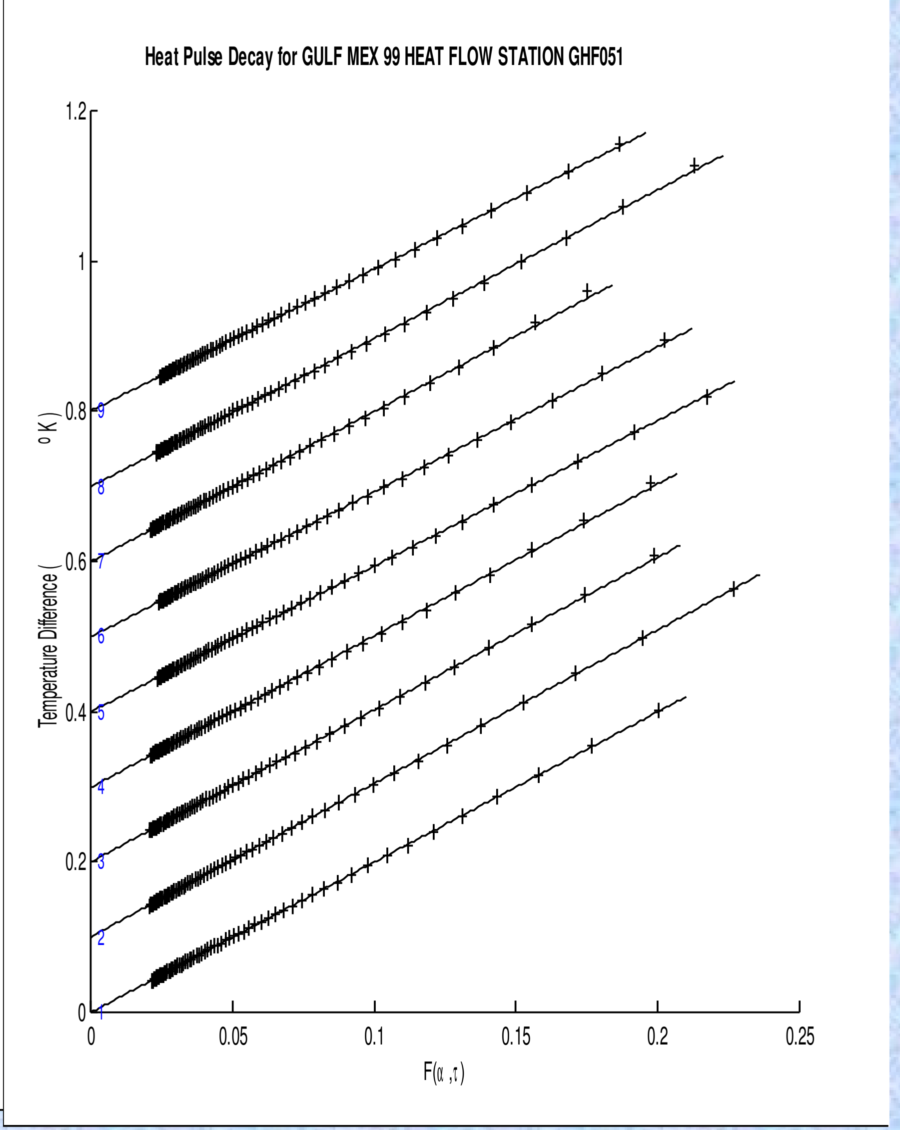
Temperature values are recorded during penetration of tube into bottom sediment

Example of temperatures for 9 thermistors recorded during penetration

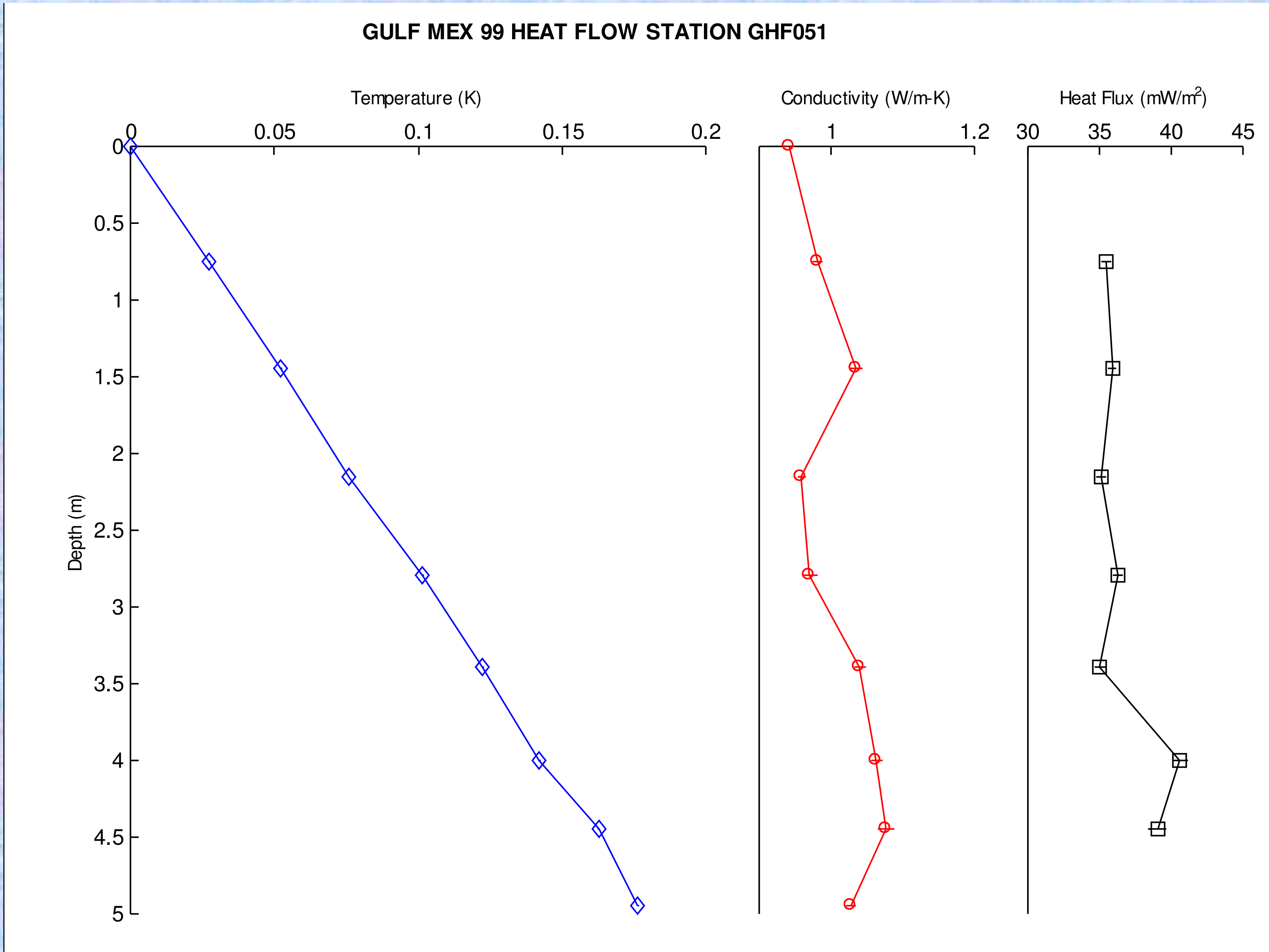


Extrapolation of temperatures to remove effect of frictional heating (left) and determination of conductivity from heat pulse (right)

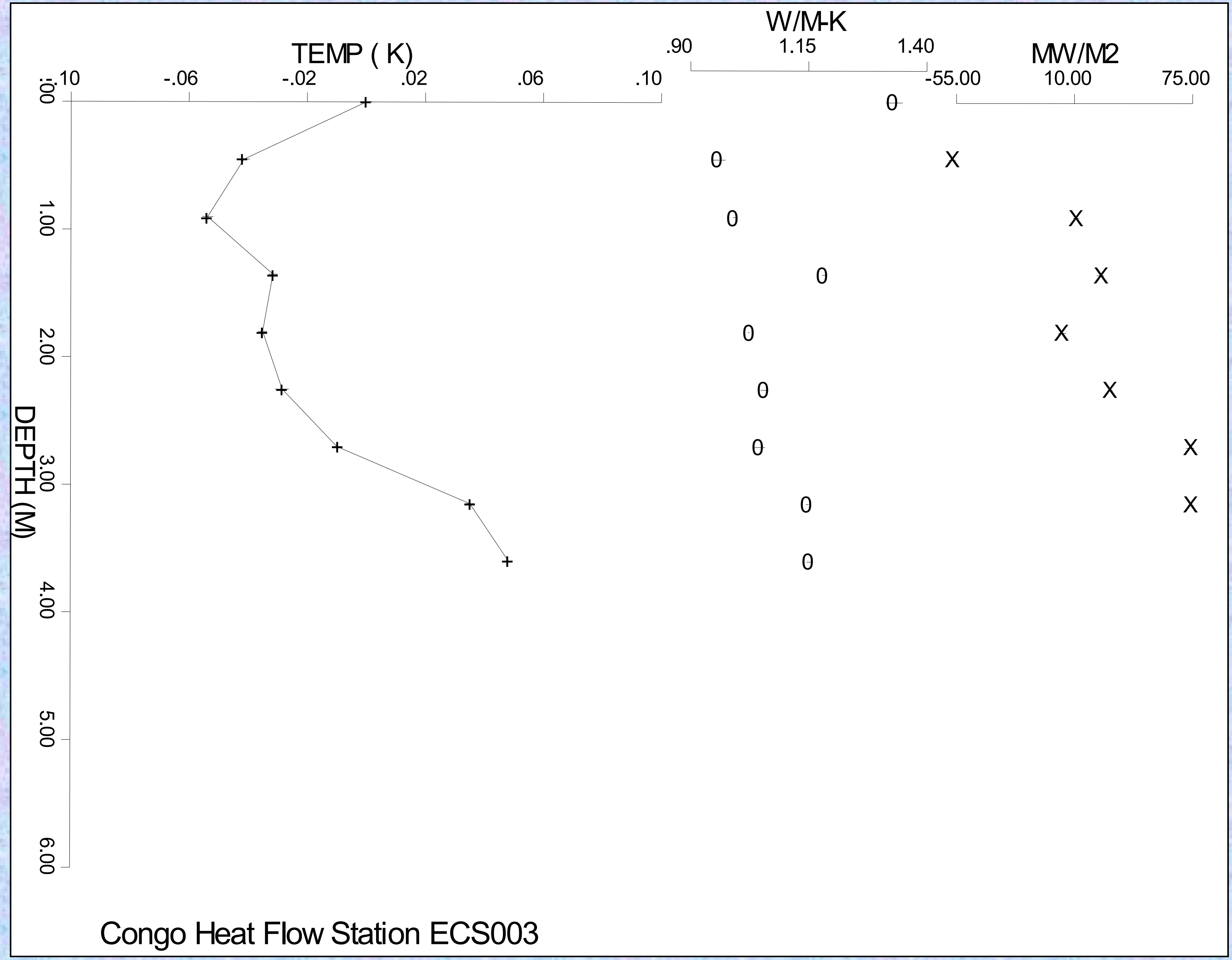




Results of temperature, conductivity and heat flow versus depth

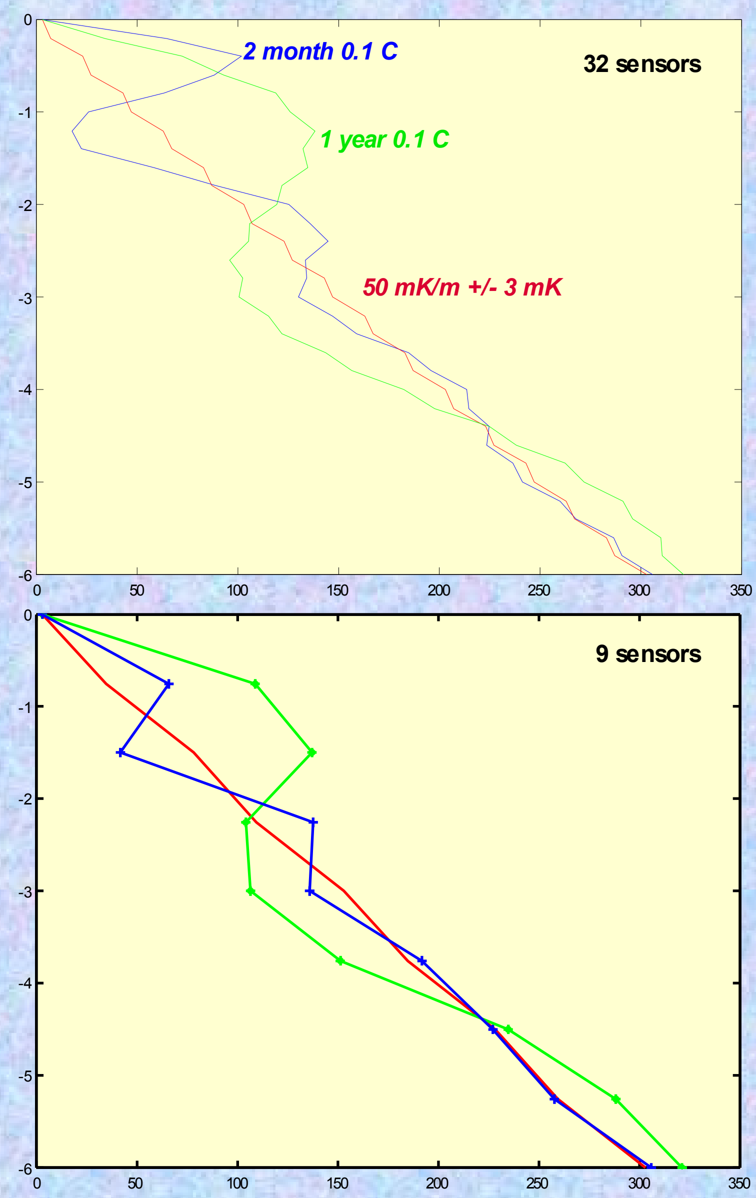


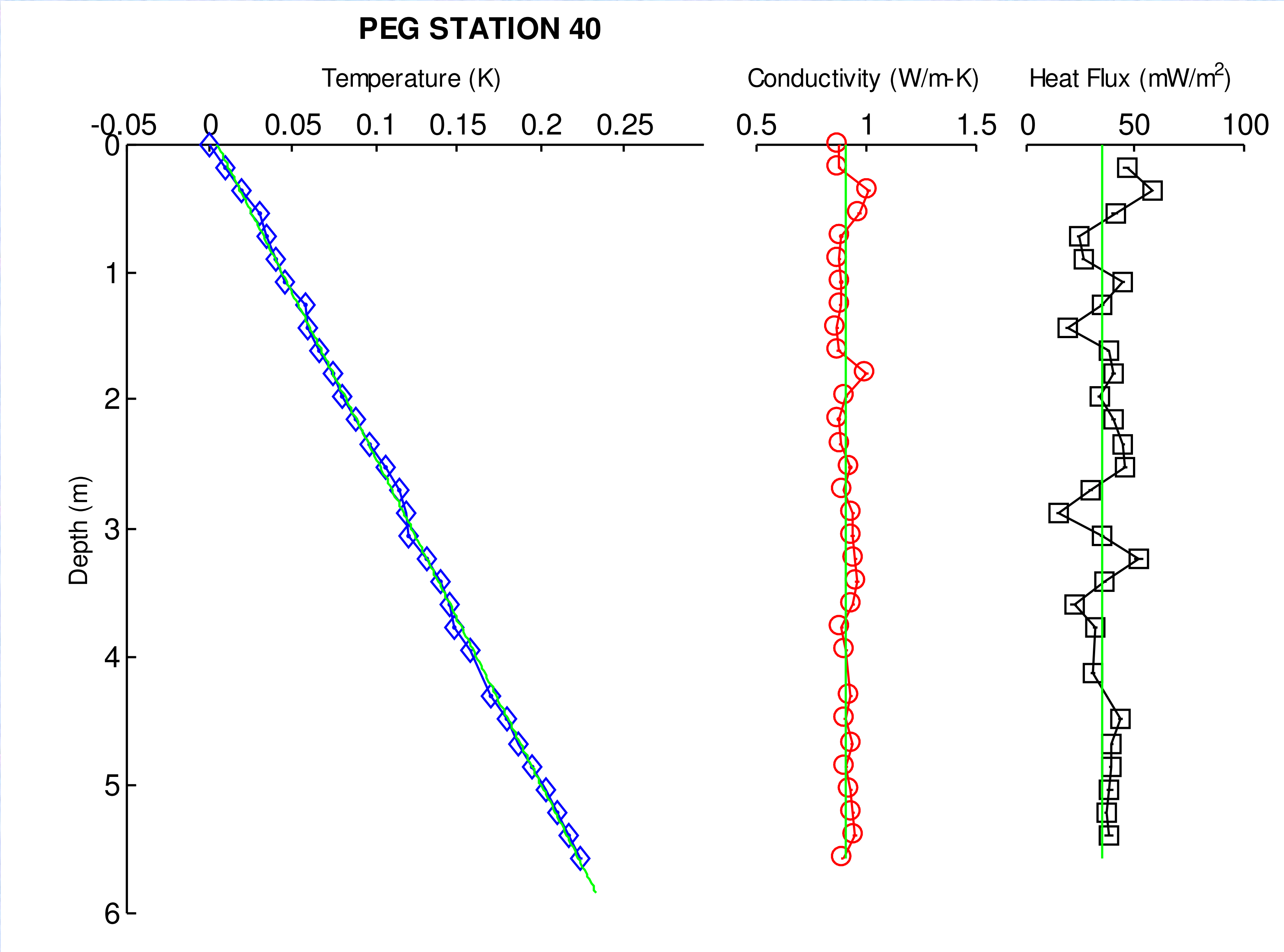
Example of disturbance due to variations in bottom-water temperature

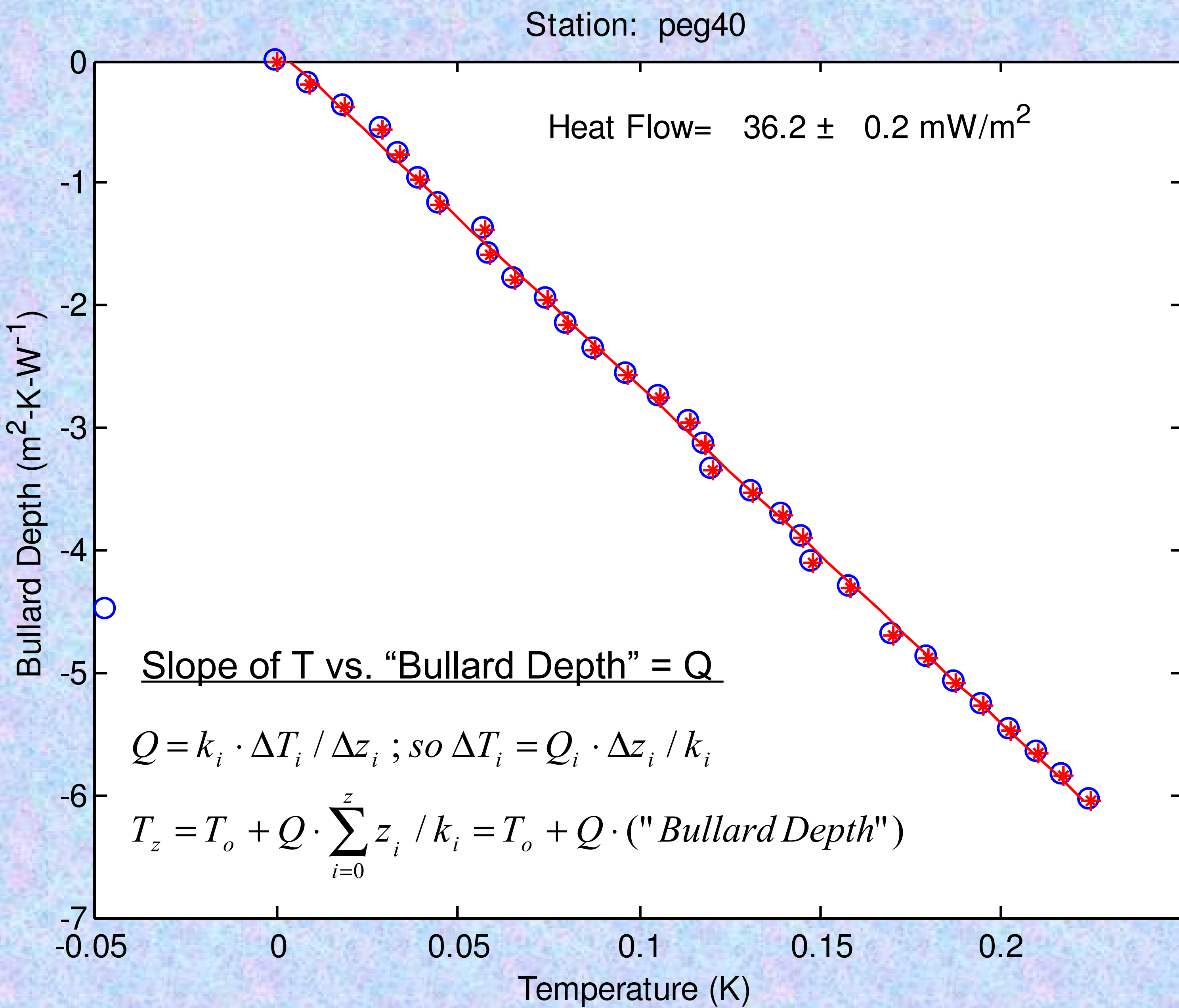


Variations in bottom-water temperature propagate down into sediment

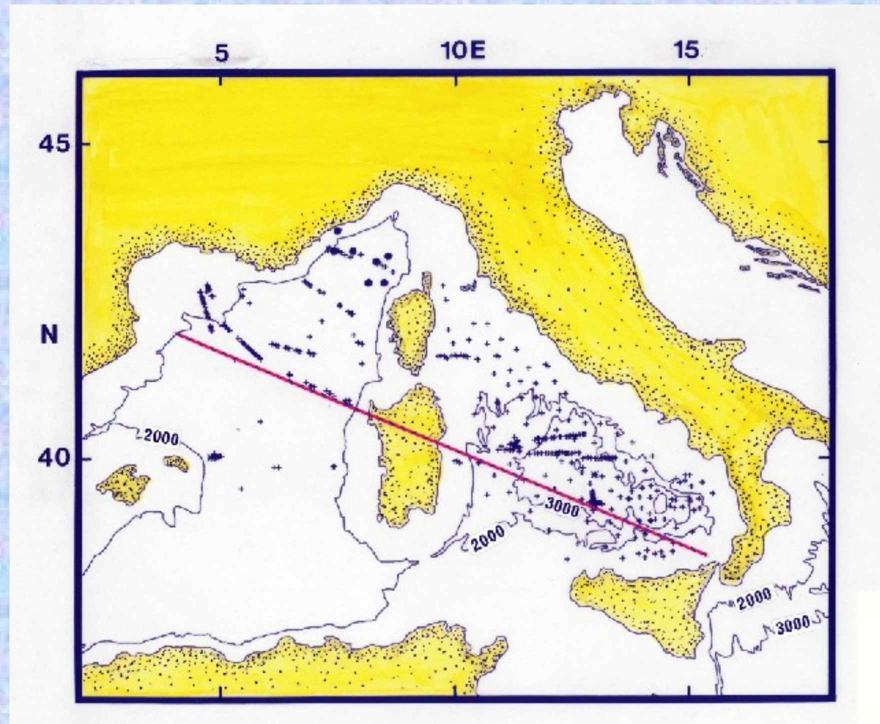
- Assume periodic changes in surface temperature of +/- 0.1 C
- Amplitude of perturbation in sediment decays depending on frequency
- Figures compare monthly vs yearly variation superimposed on constant gradient as recorded on 9 and 32 sensors over depth of 6 m
- In shallow water, variations can become large!



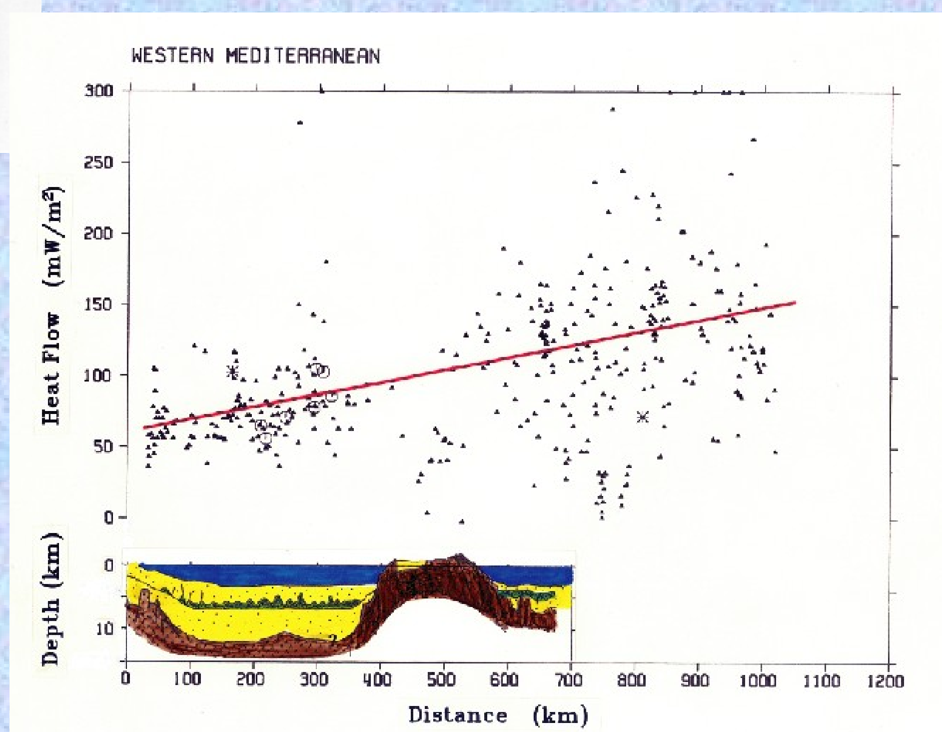

PEG STATION 40
Temperature (K)
Conductivity (W/m-K)
Heat Flux (mW/m^2)
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.5
1
1.5
0
50
100
Depth (m)
0
1
2
3
4
5
6



Station: peg40
Heat Flow= 36.2 ± 0.2 mW/m2
Slope of T vs. "Bullard Depth" = Q
$Q = k_i \cdot \Delta T_i / \Delta z_i$; $so\ \Delta T_i = Q_i \cdot \Delta z_i / k_i$
$T_z = T_o + Q \cdot \sum_{i=0}^{z} z_i / k_i = T_o + Q \cdot ("Bullard\ Depth")$
Bullard Depth (m2-K-W-1)
Temperature (K)
0
-1
-2
-3
-4
-5
-6
-7
-0.05
0
0.05
0.1
0.15
0.2



Example of basin-scale values of heat flow in Western Mediterranean



Values increase from W→E across basin due to decreasing age of rifting

References

- Beardsmore, G.R. and Cull, J.P., Crustal Heat Flow: A Guide to Measurement and Modelling, Cambridge University Press, 2001.
- Wright, J.A. and Louden, K.E., Handbook of Seafloor Heat Flow, CRC Press, 1989.

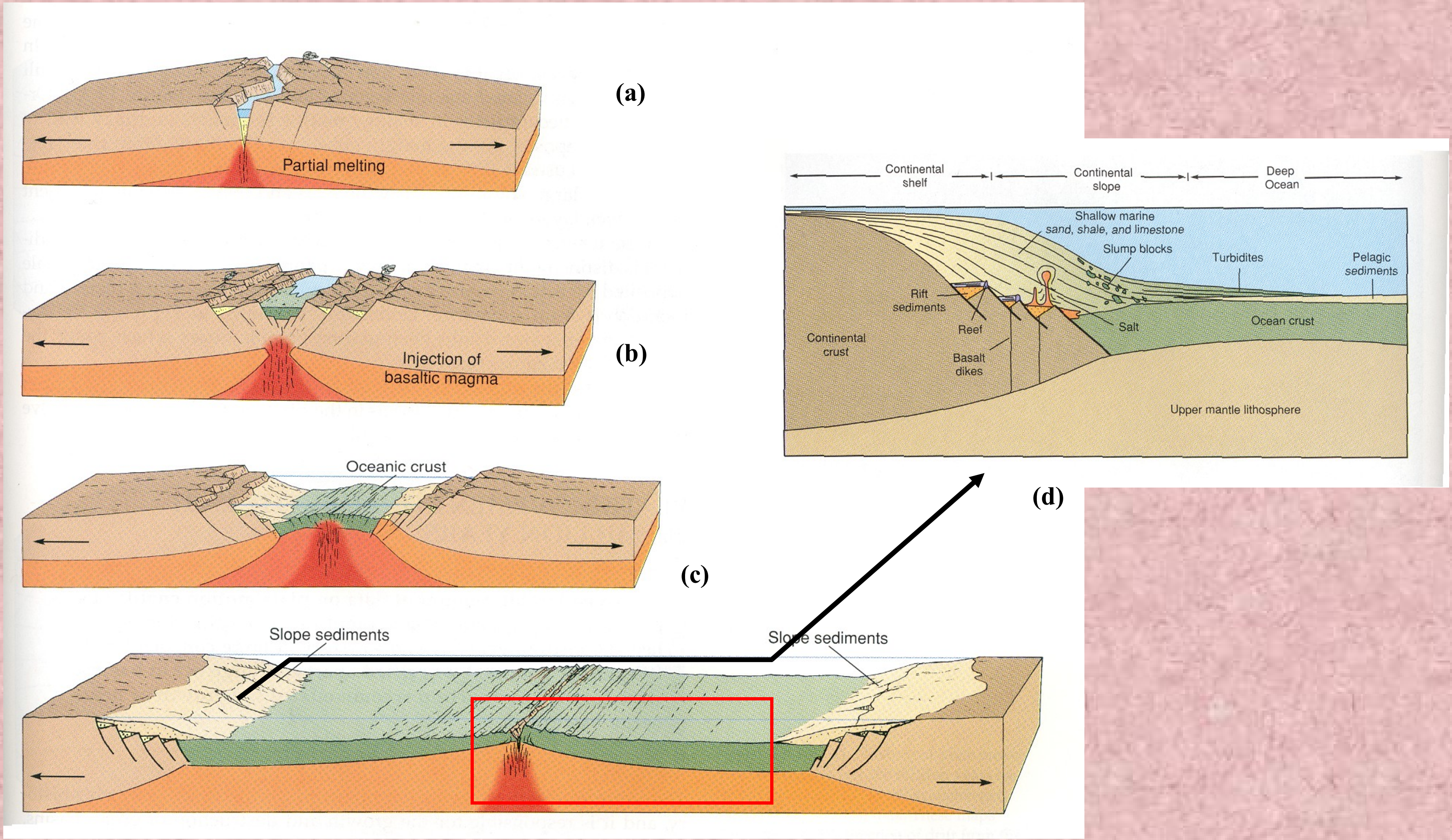
Rifting Models: Pure and Simple

Thingvellir, Iceland

www.cas.sc.edu/.../Iceland_MidOceanRdg.jpg

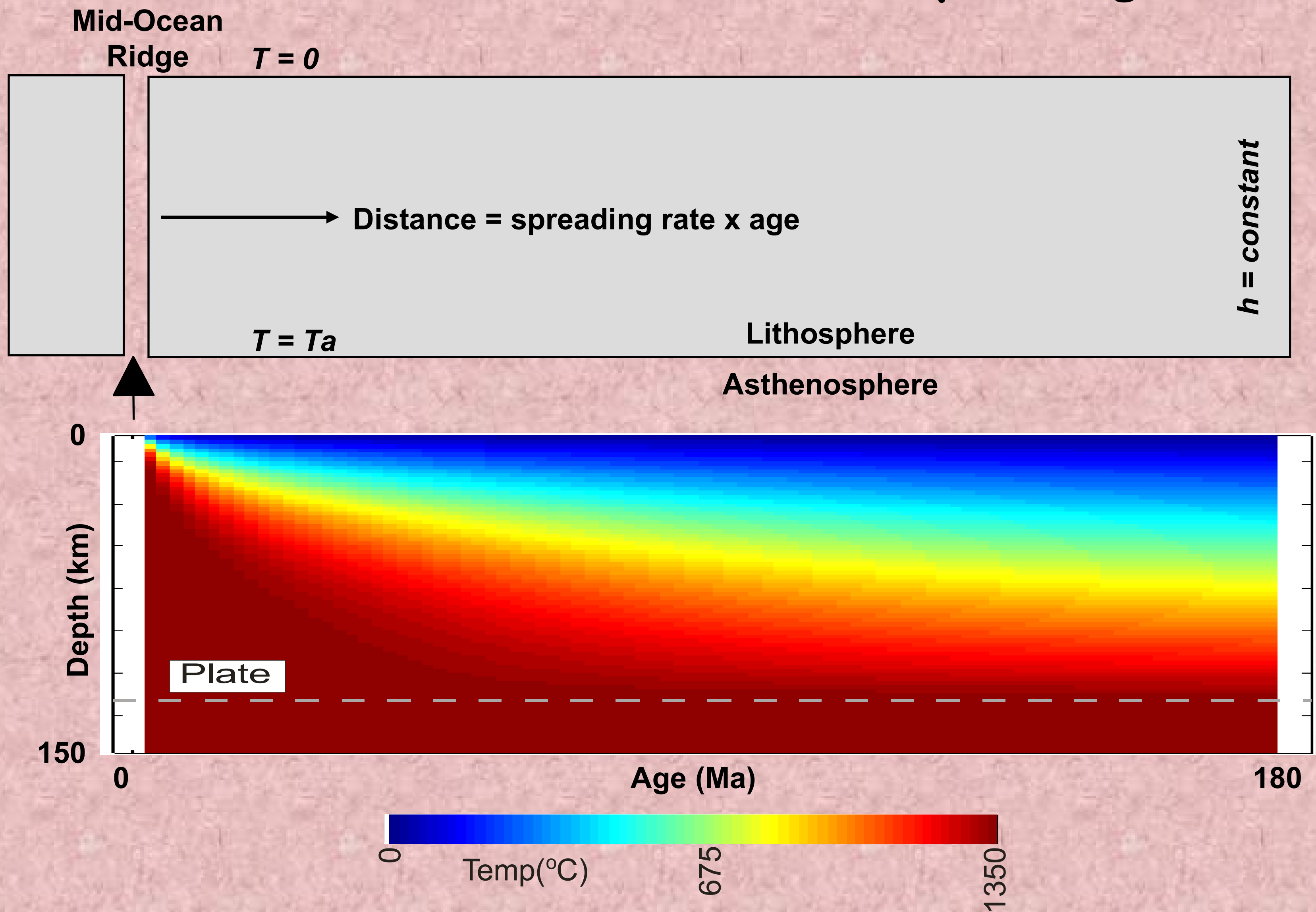
Great Rift Valley, Kenya

www.dogspit.net/Beautiful_Rift_Valley.jpg

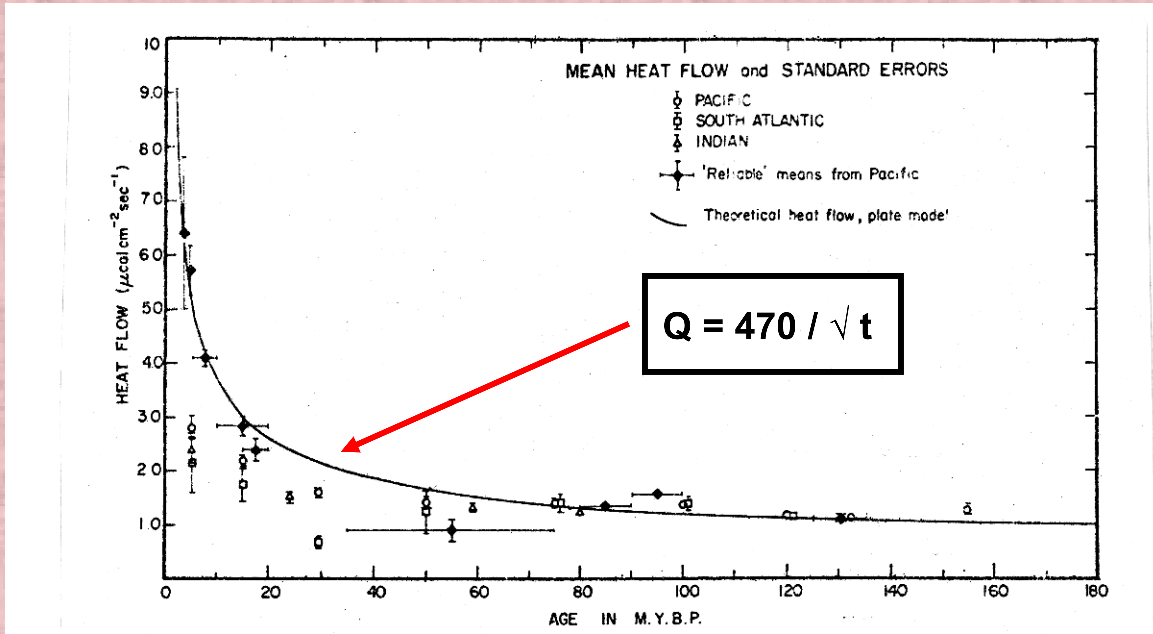


Stages in the evolution of a rifted margin. (a) Continental rifting begins when the crust is uplifted and stretched with occurrence of block faulting. Syn-rift sediment accumulates in the depressions of the downfaulted blocks. Basaltic magma is injected into the rift system. (b) Rifting continues, the continental crust is broken, oceanic crust begins to form and a narrow arm of the ocean invades the rift zone. (c) The ocean basin widens. Remnants of continental sediment are preserved in the down-dropped blocks of the continental margins. (d) Structural features of a fully formed rifted margin. Tilted fault blocks and continental sedimentary deposits consisting of alluvial fans and evaporites define the margins of continental crust. As the continent subsides, reefs and beach and lagoon sediments are deposited. Eventually the entire margin is covered by a thick sediment accumulation grading from shallow-marine into deep ocean. Poorly-sorted sandstones and shales are deposited by turbidity currents into the deep water basin.

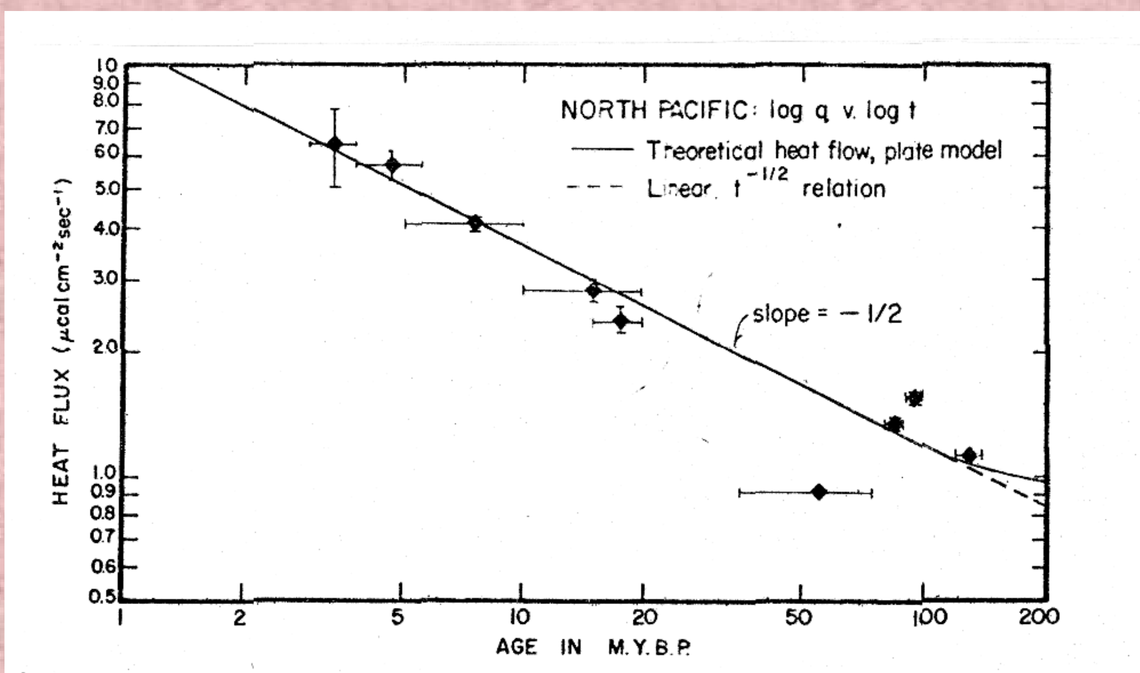
Plate Model for sea-floor spreading



Heat Flow decreases exponentially in a simple relationship with age



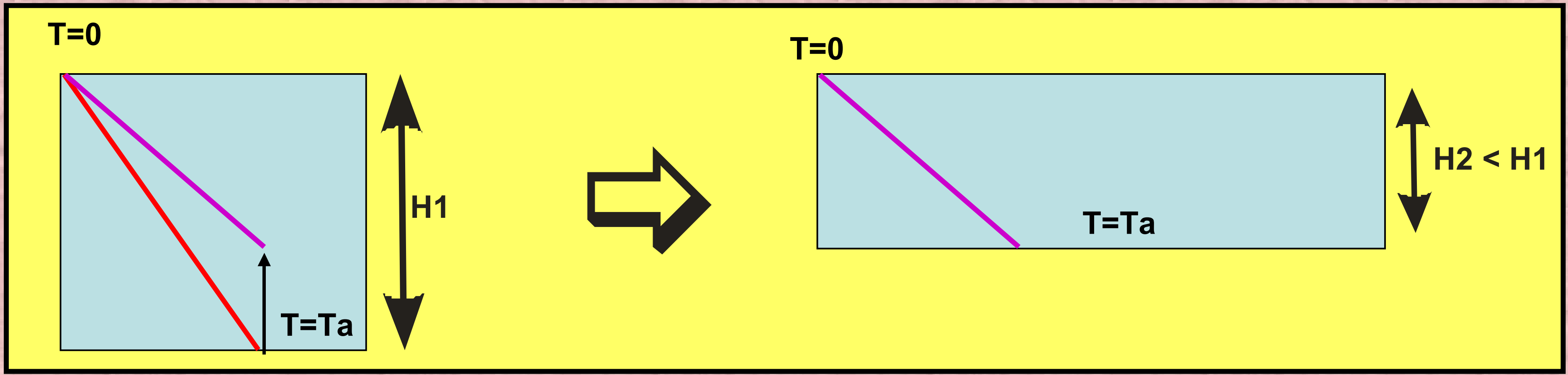
Standard heat flow averages plus more selective "reliable" means plotted as a function of age and compared to predictions of the plate model.



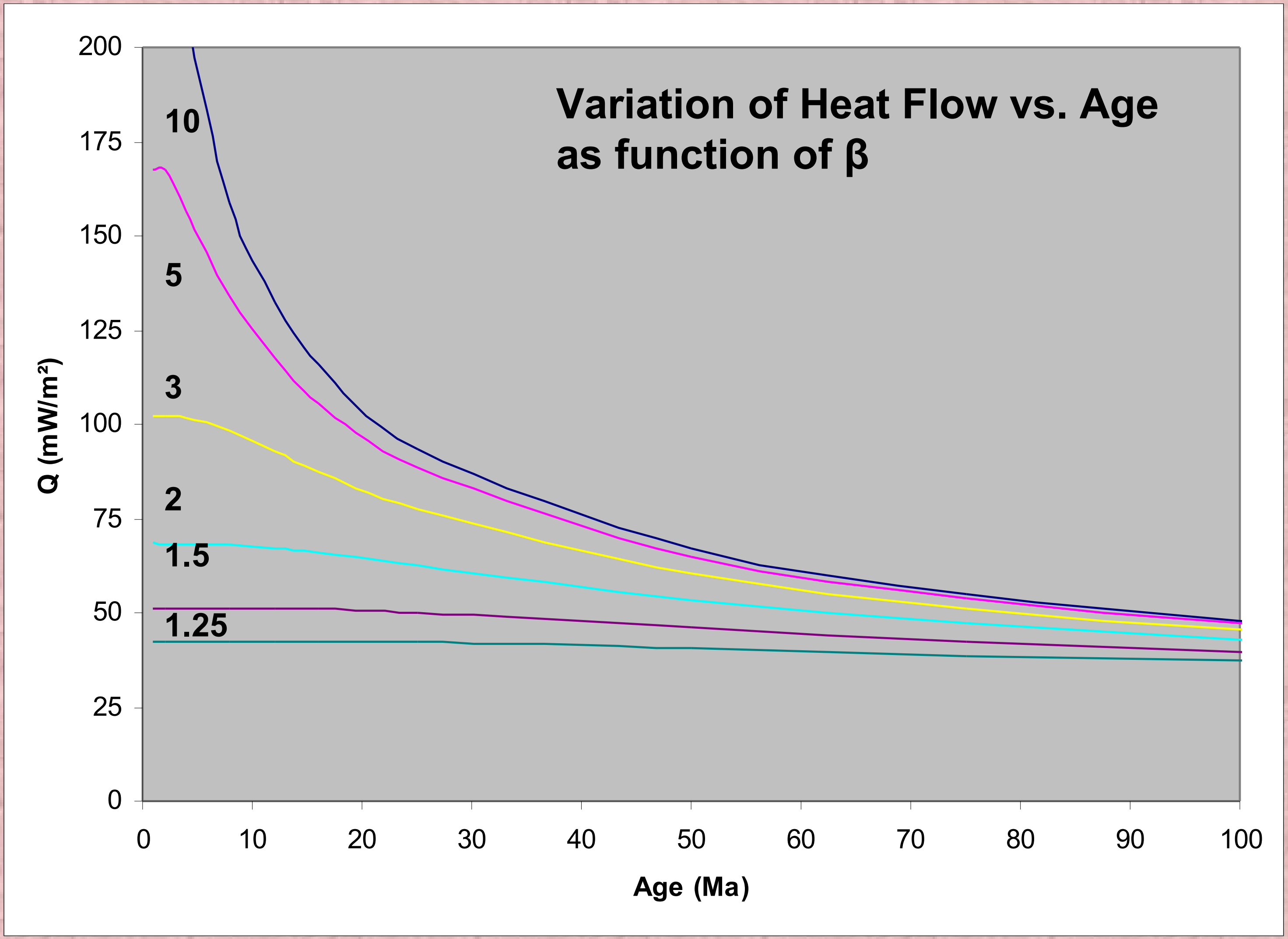
The reliable heat flow means plotted versus age on a logarithmic scale. The theoretical heat flow curves have a slope of -1/2 until an age of about 120 Ma, after which the plate model no longer follows the linear trend.

What happens across rifted margins?

- *Lithosphere is only partly thinned and extended at time of rifting, t=0.*
- *Thermal gradient increases as base of lithosphere moves up, so Heat flow increases as H decreases.*
- *We define a "stretching factor", Beta, where $\beta = L2/L1 = H1/H2$. For oceanic rifting, $\beta = \infty$.*
- *Possible to have multiple episodes of extension during margin evolution*

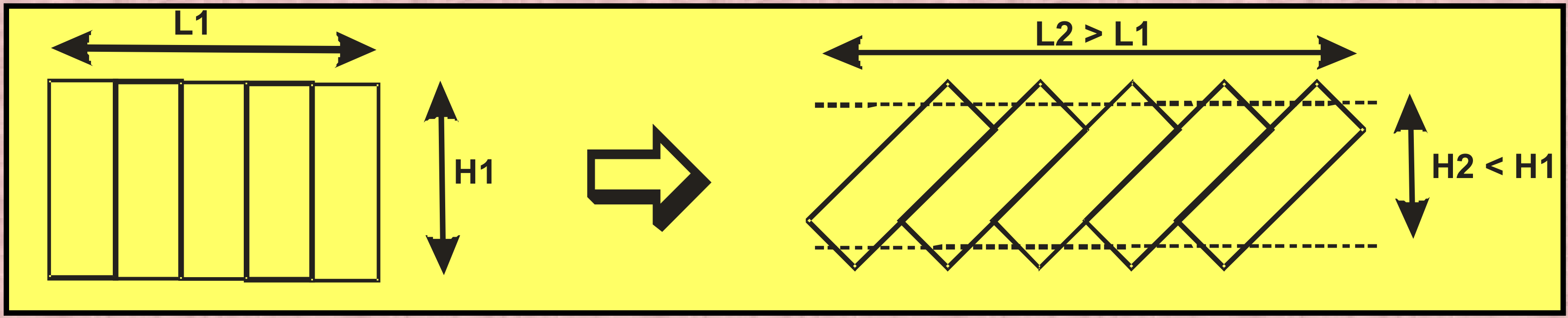


Pure Shear Rifting: Uniform Lithosphere

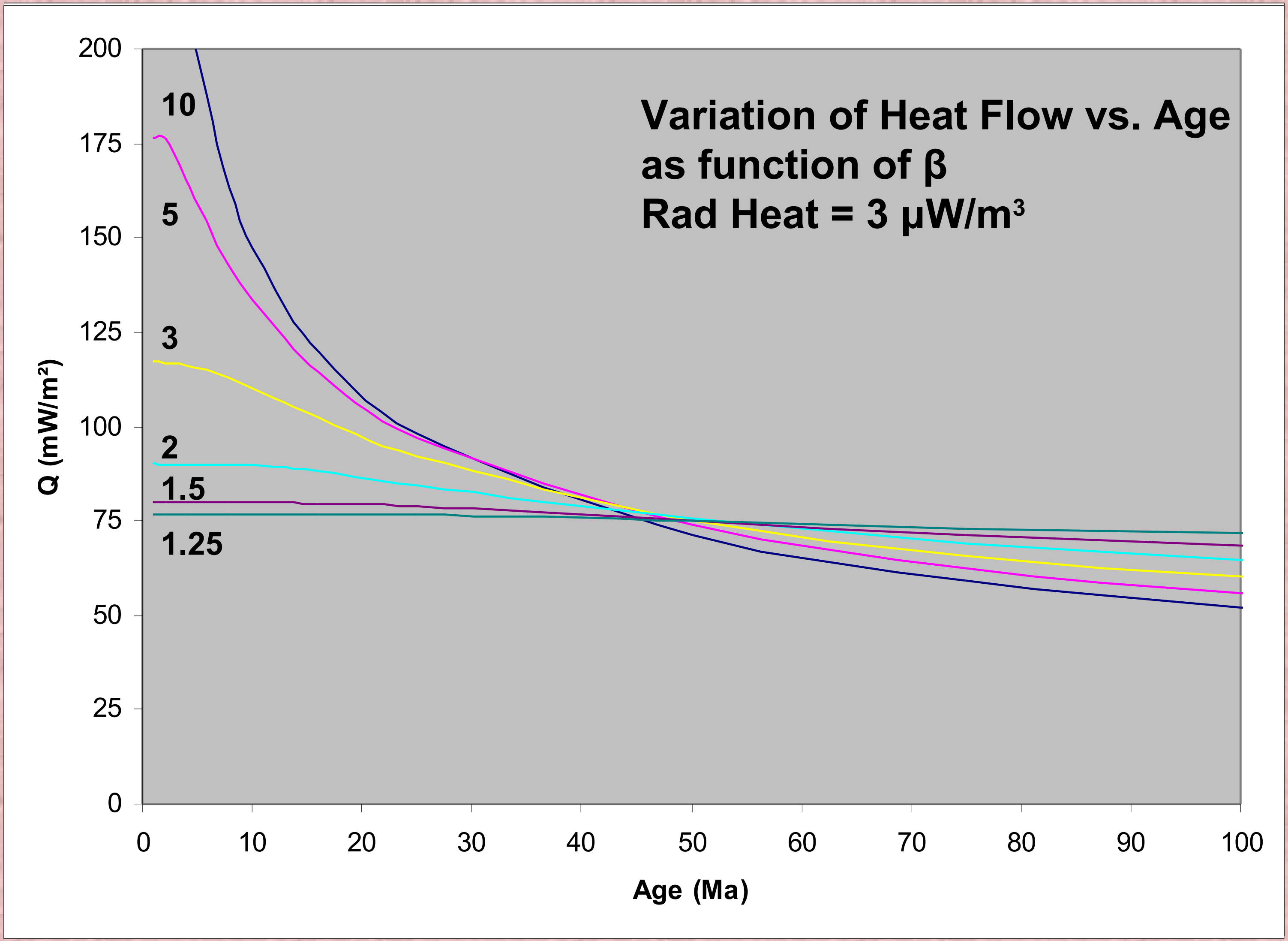


What about crustal thinning?

- *Assume crust thins in same ratio as lithosphere but by brittle faulting*
- *Tilting deck of cards analogy -> tilted fault blocks*
- *Additional effect due to reduction of radiogenic heat as continental upper crust thins*

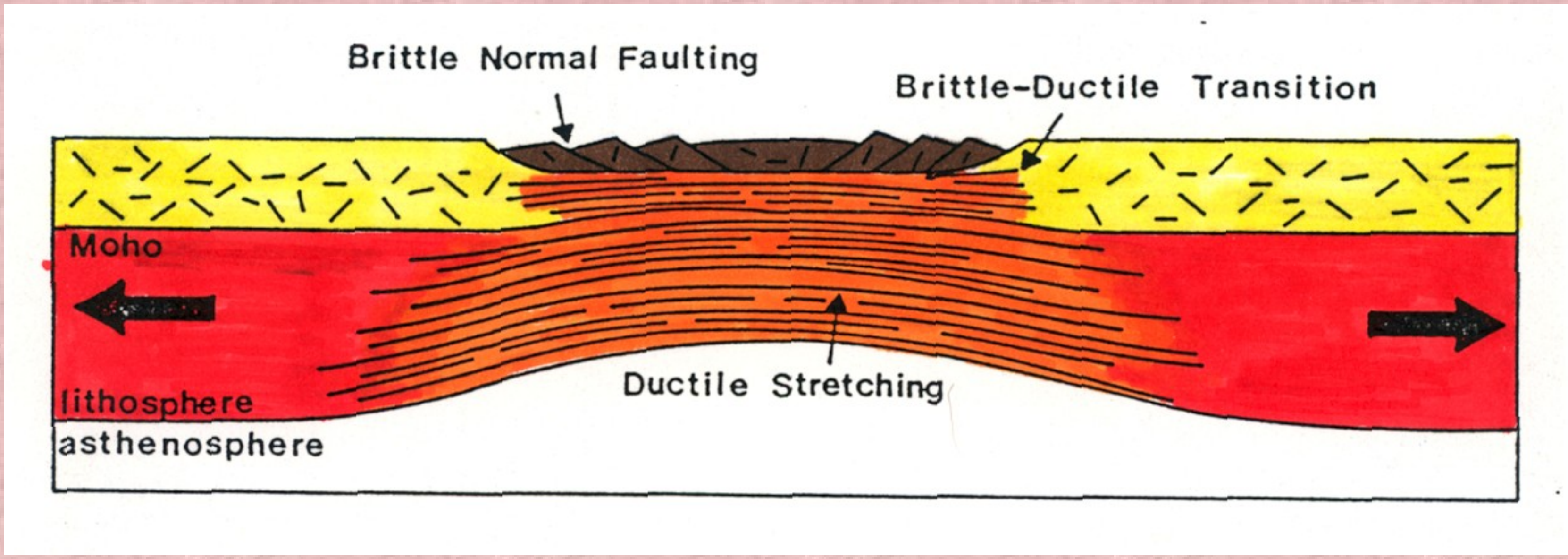


Pure Shear Rifting: Lithosphere + Crust



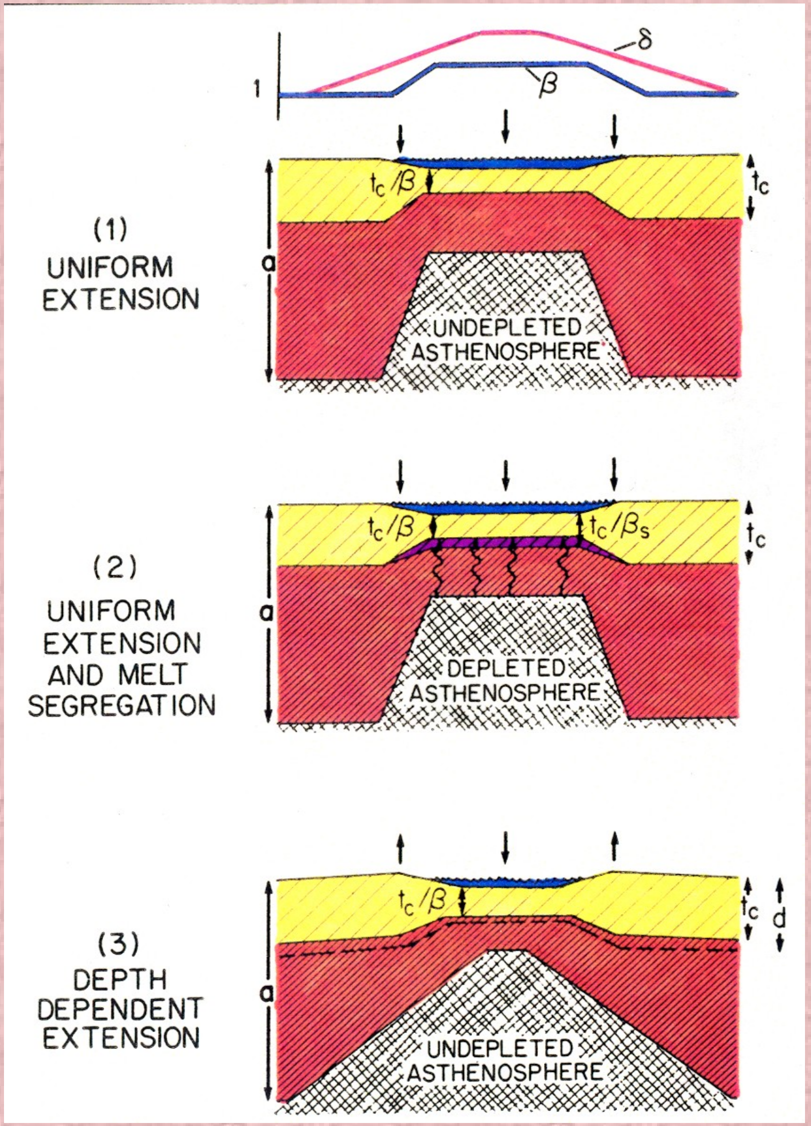
Do Upper Crust + Lithosphere Thin in Same Ratio?

Not necessarily if decoupling between brittle and ductile layers, esp. at high values of extension

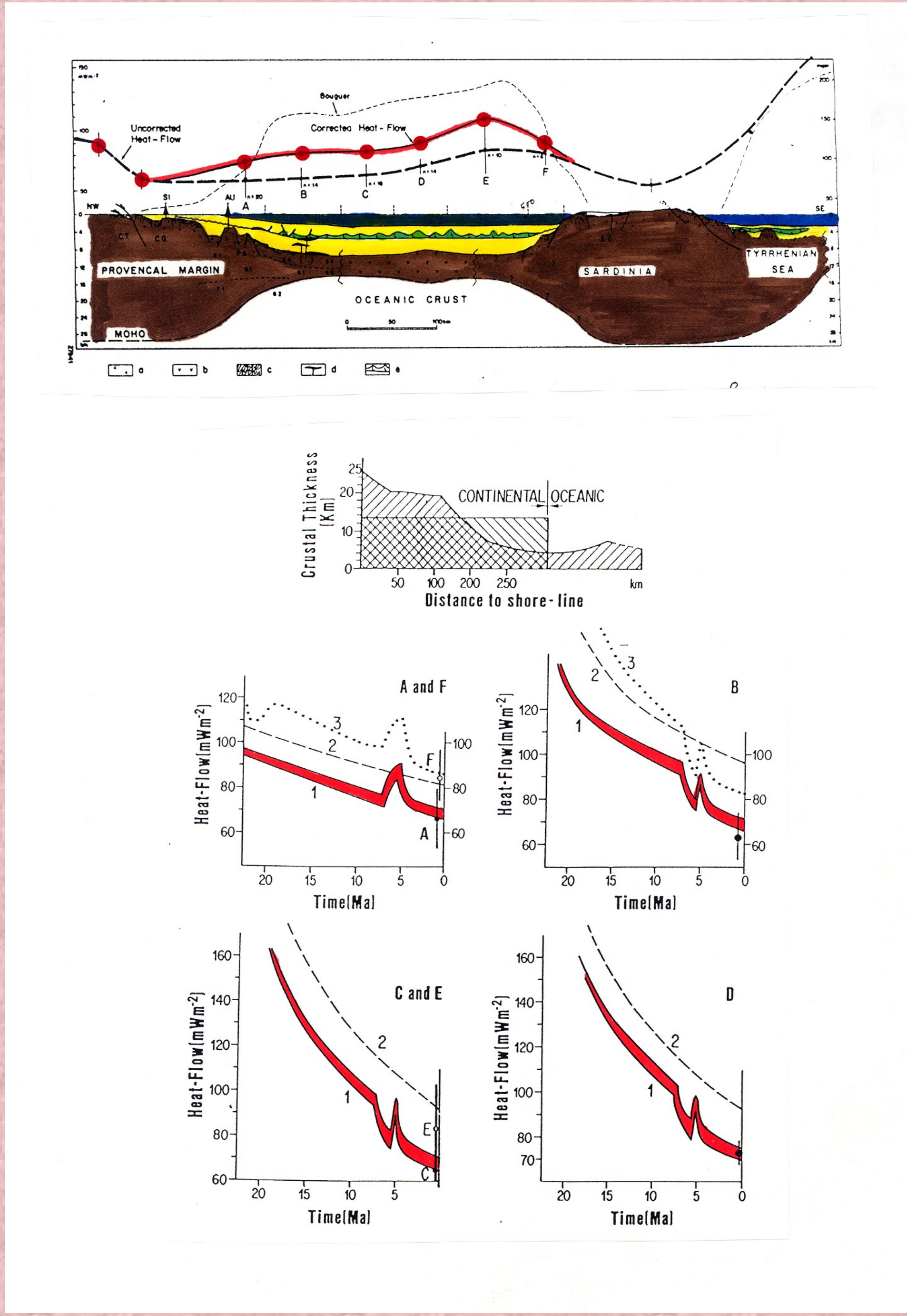


More Complex Models

- Separation of upper and lower lithosphere: (e.g. crust and mantle) with uniform or non-uniform extension
- Allows for non-symmetric margins by variations in β vs. δ
- Addition of melt
- Include variations in time and distance across margin as functions of rheology



Example of models for Western Med constrained by heat flow



from Burrus et al., 1987. Heat flow, subsidence and crustal structure of the Gulf of Lions, CSPG Mem 12

A more recent reference

Understanding the thermal evolution of deep-water continental margins

Nicky White, Mark Thompson & Tony Barwise

NATURE | VOL 426 | 20 NOVEMBER 2003

Areas of exploration for new hydrocarbons are changing as the hydrocarbon industry seeks new resources for economic and political reasons. Attention has turned from easily accessible onshore regions such as the Middle East to offshore continental shelves. Over the past ten years, there has been a marked shift towards deep-water continental margins (500–2,500 m below sea level). In these more hostile regions, the risk and cost of exploration is higher, but the prize is potentially enormous. The key to these endeavours is a quantitative understanding of the structure and evolution of the thinned crust and lithosphere that underlie these margins.

4D THERMAL MODELLING:
AN EXAMPLE FROM THE CENTRAL SCOTIAN SLOPE IN AND AROUND THE EASTERN SHELBURNE SUB-BASIN

Eric Negulic, Hans Wielens, Keith Louden, Mladen Nedimovic

GX TECHNOLOGY
An I/O Company

IES GmbH

Outline

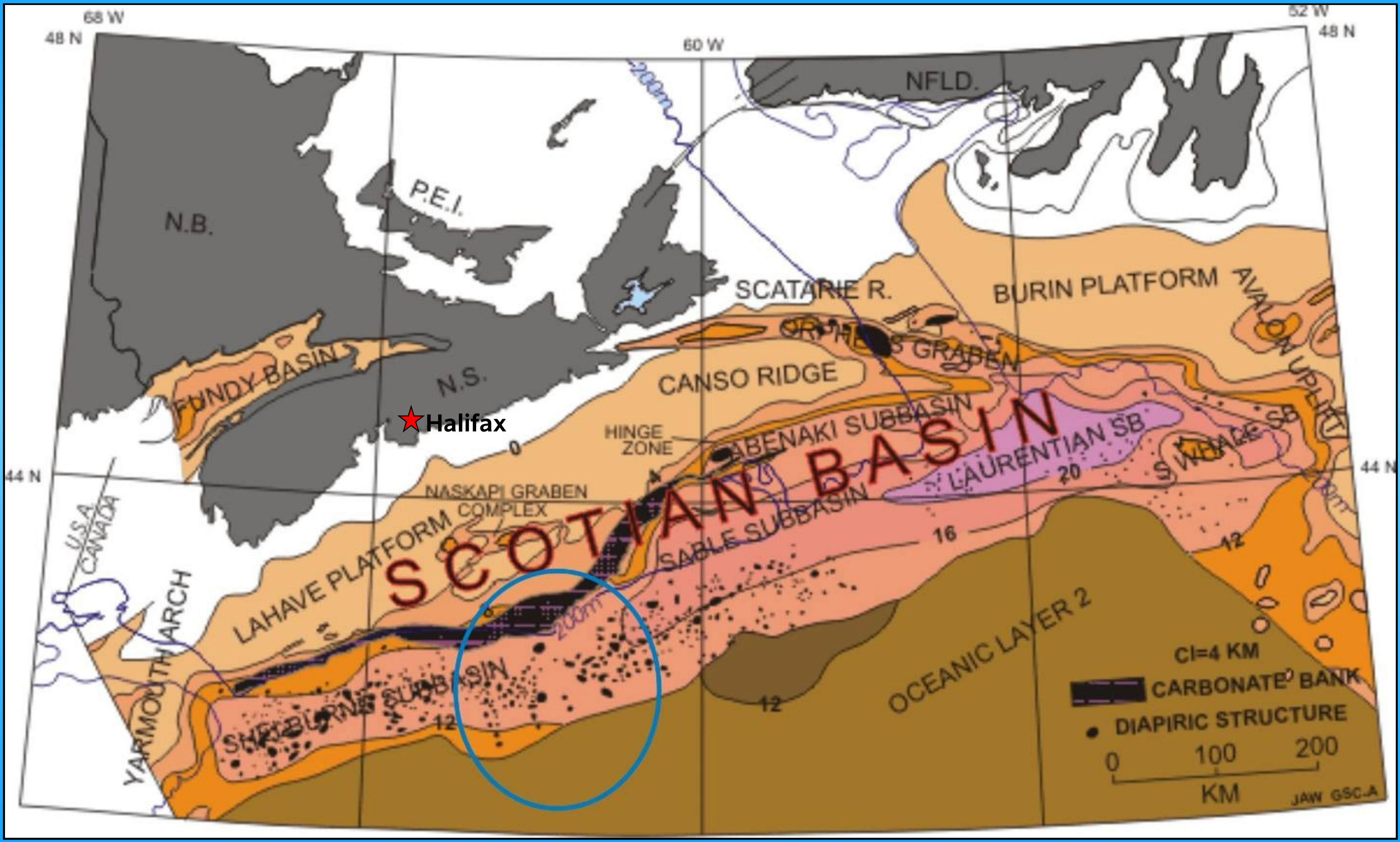
Presentation Overview

- Introduce Study Area
- Brief Overview of Scotian Basin Stratigraphy
- Seismic Interpretation as Basis for Heat-flow Modelling
- Thermal Modelling
  - Surface heat-flow
  - Cross sectional heat-flow
  - Selecting locations for future measurements

Project Goals

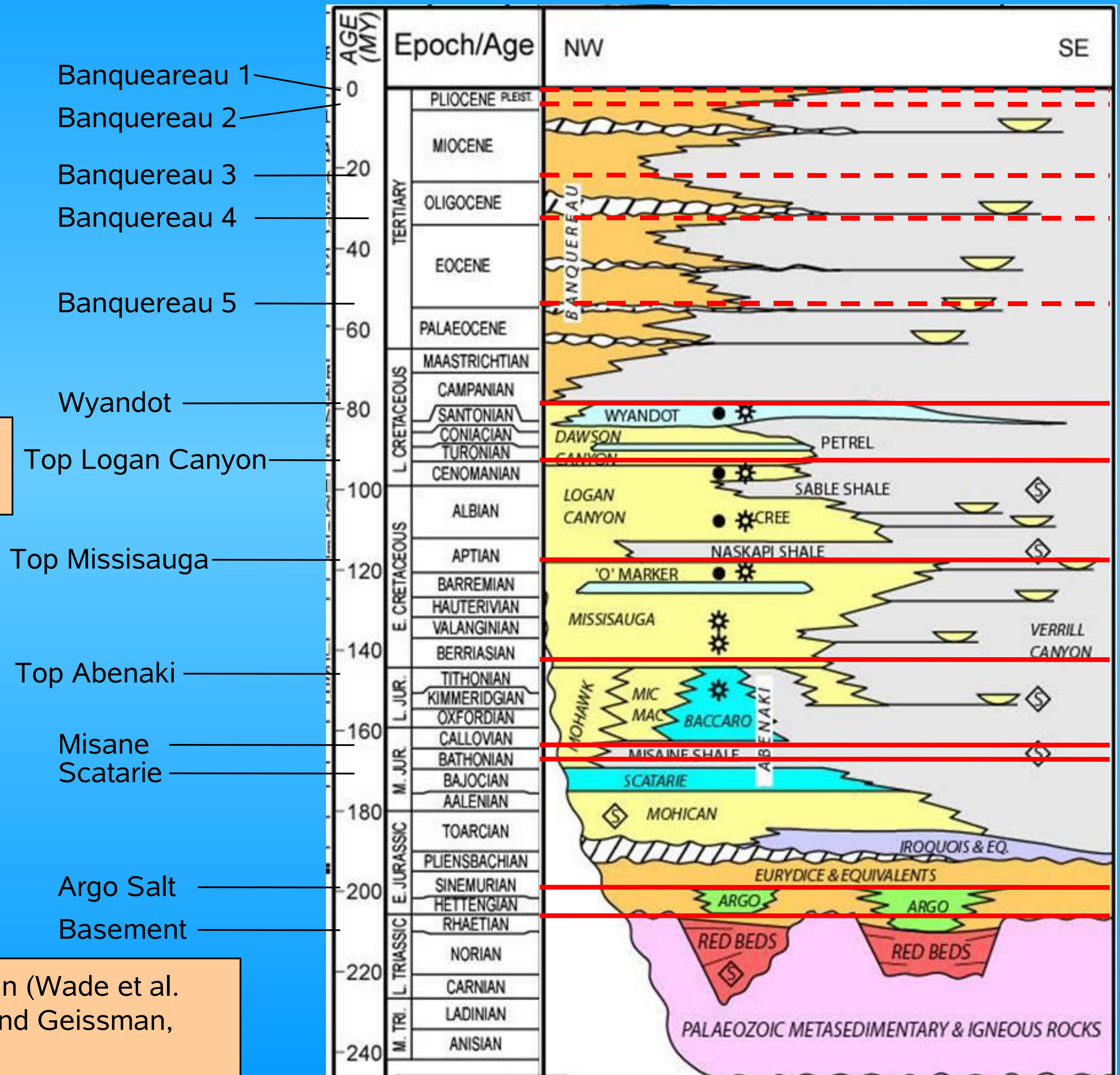
- Interpret the effects of salt diapirs on heat-flow
- Constrain regions for future heat-flow measurements

Study Area



Overview of the Scotian Basin with study area in blue (modified from from http://gsc.nrcan.gc.ca)

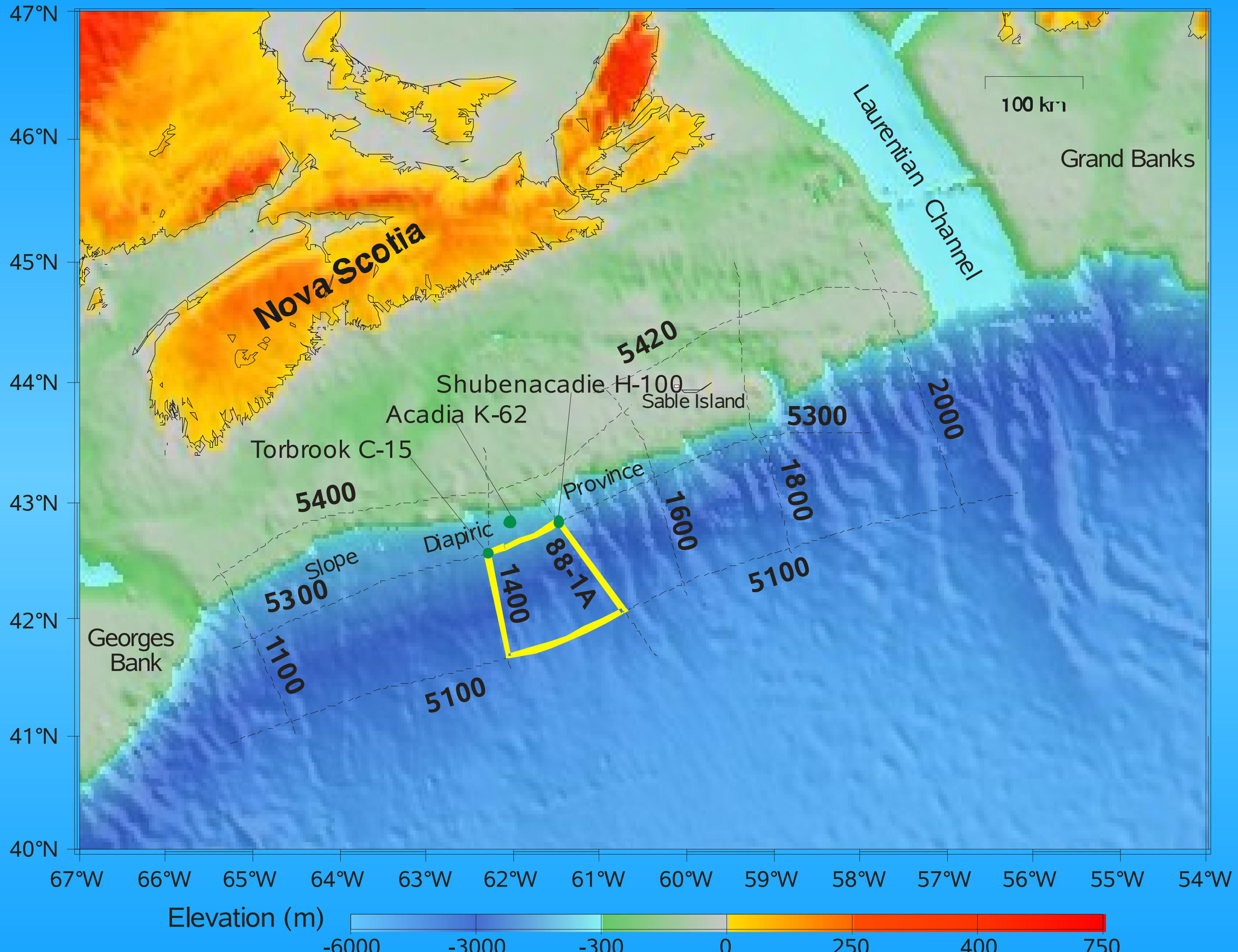
Scotian Basin Stratigraphy



Stratigraphic units present in seismic interpretations

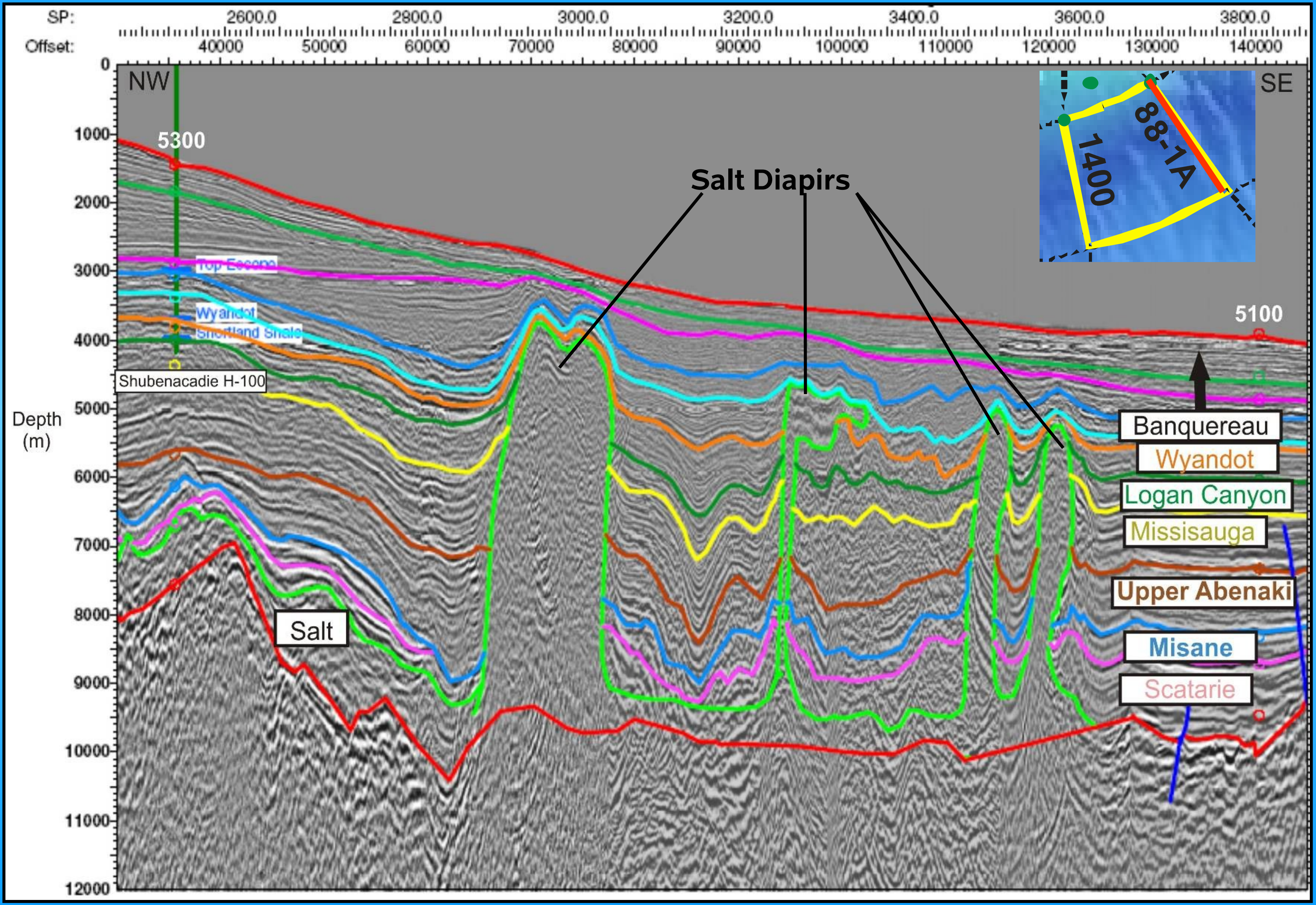
Stratigraphy of the Scotian Basin (Wade et al. 1995, time scale after Palmer and Geissman, 1999)

Seismic interpretations

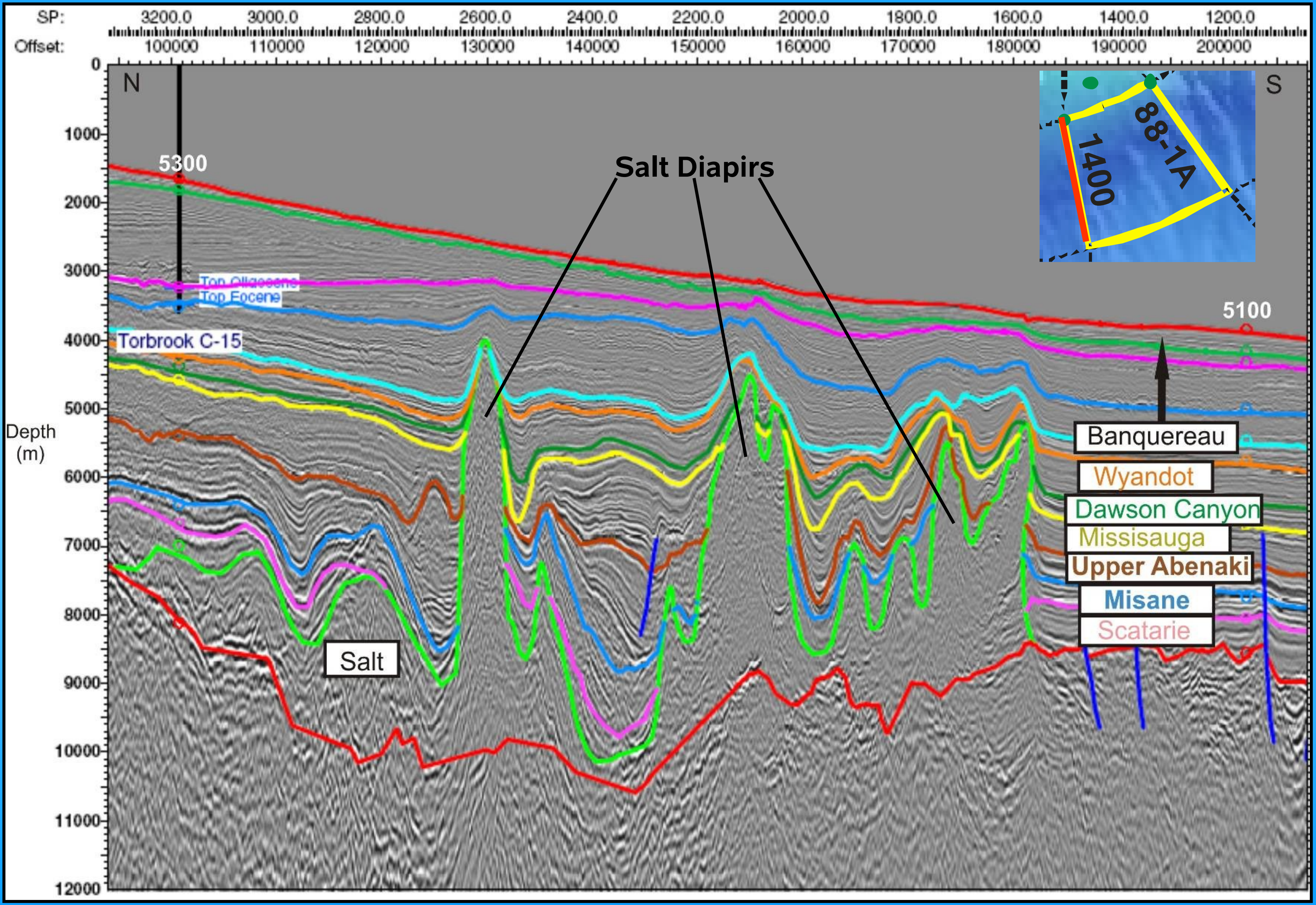


Location of GXT NovaSPAN lines and Lithoprobe line 88-1a. Yellow lines represent interpreted sections, green dots represent well locations (modified from Keith Louden personal communication)

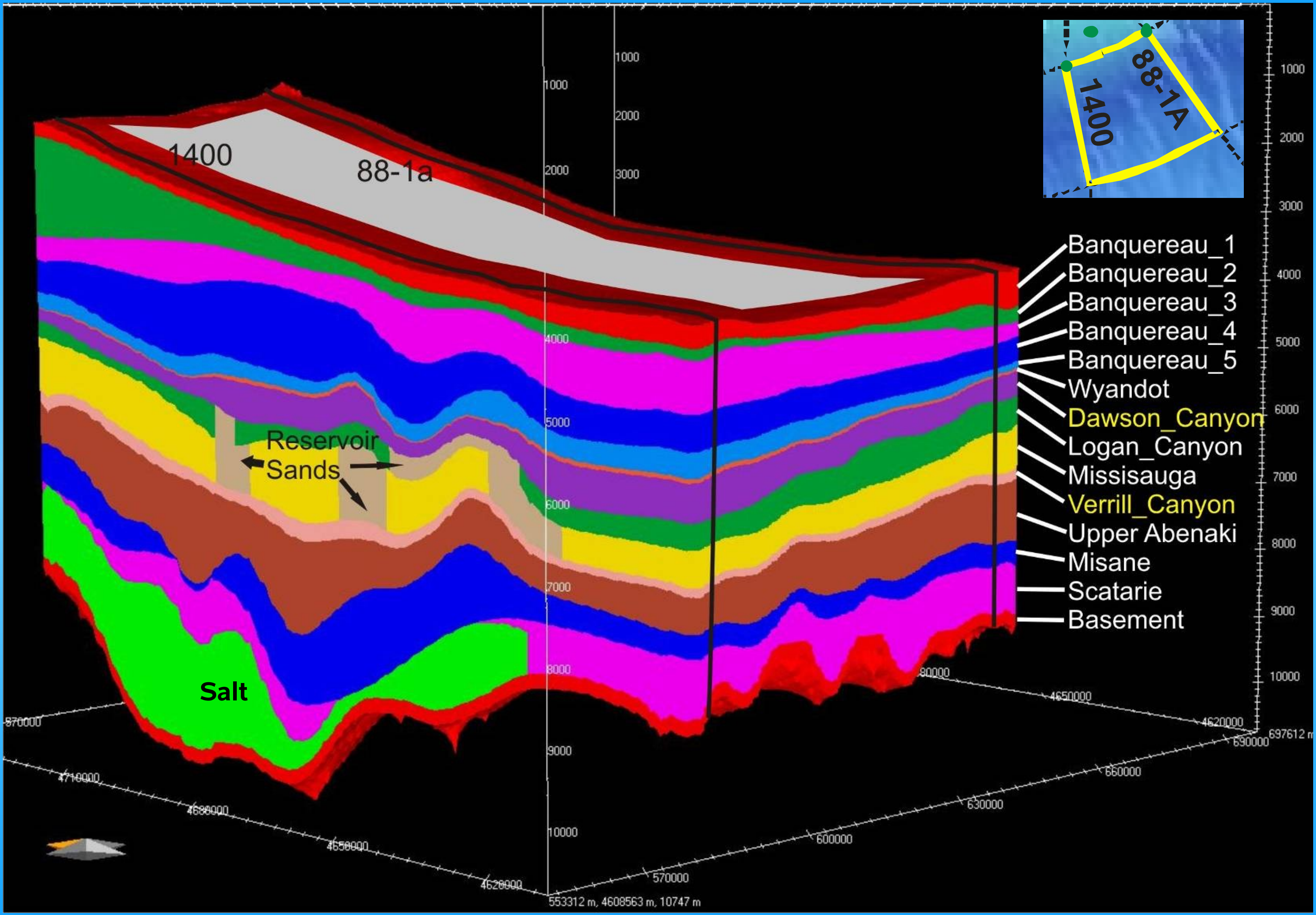
Seismic line 88-1a



Seismic line 1400



Thermal and petroleum systems modelling



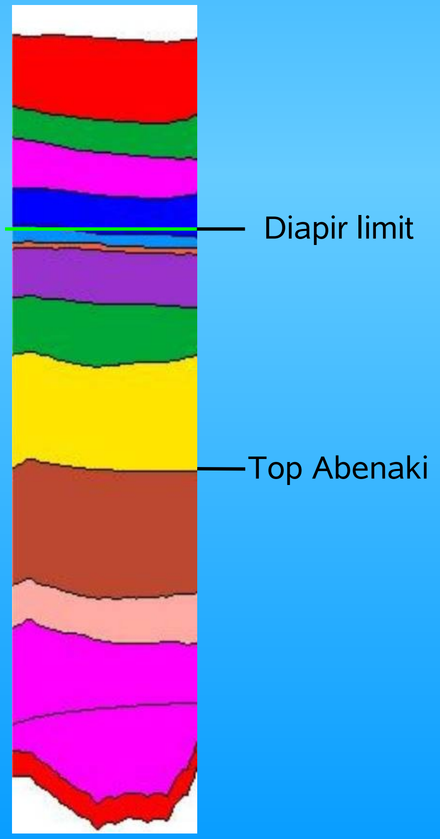
3D view of model created in PetroMod

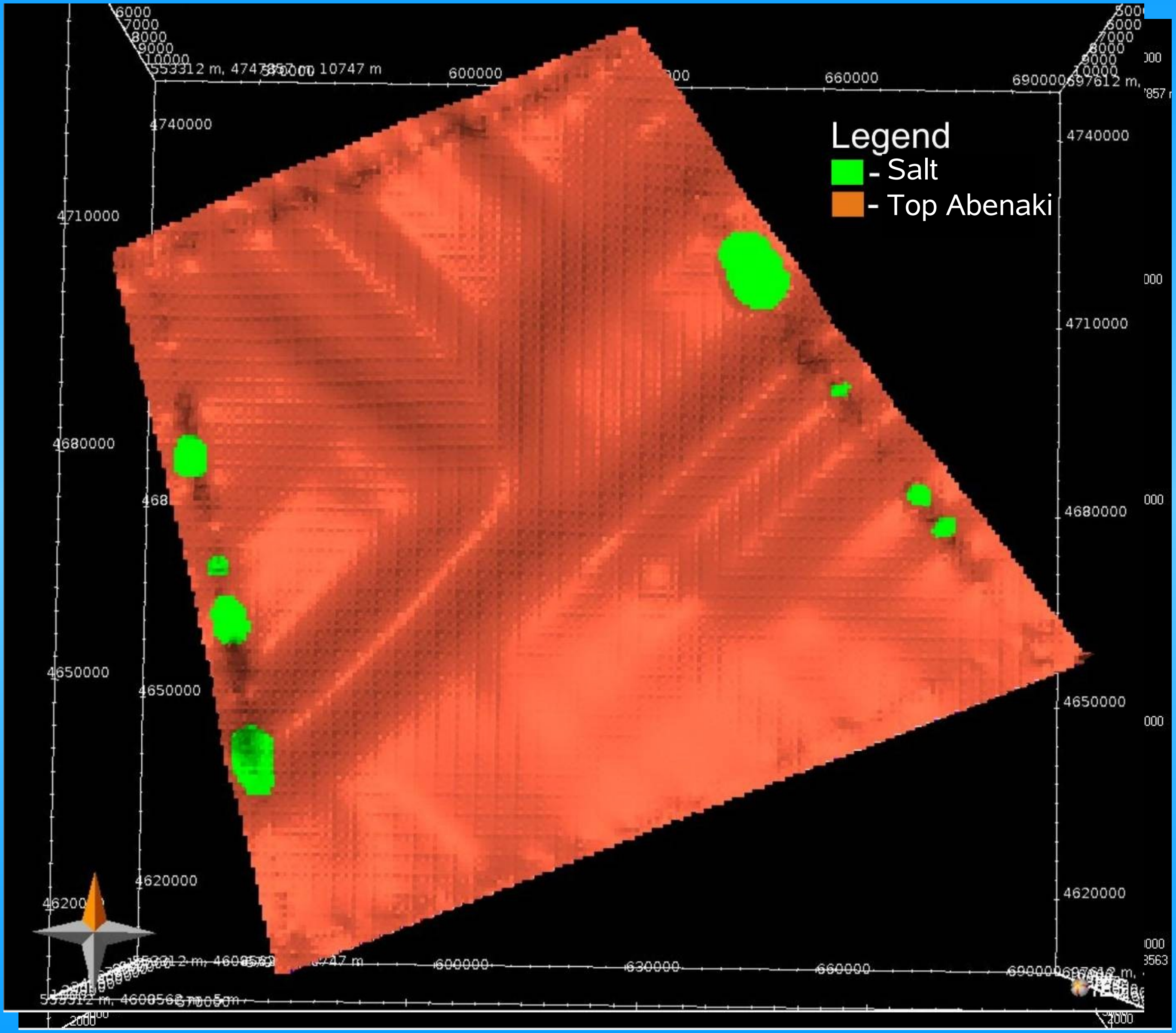
Thermal Modelling

<u>Surface heat-flow trends</u>

- General heat-flow of ~45-55 mW/m²

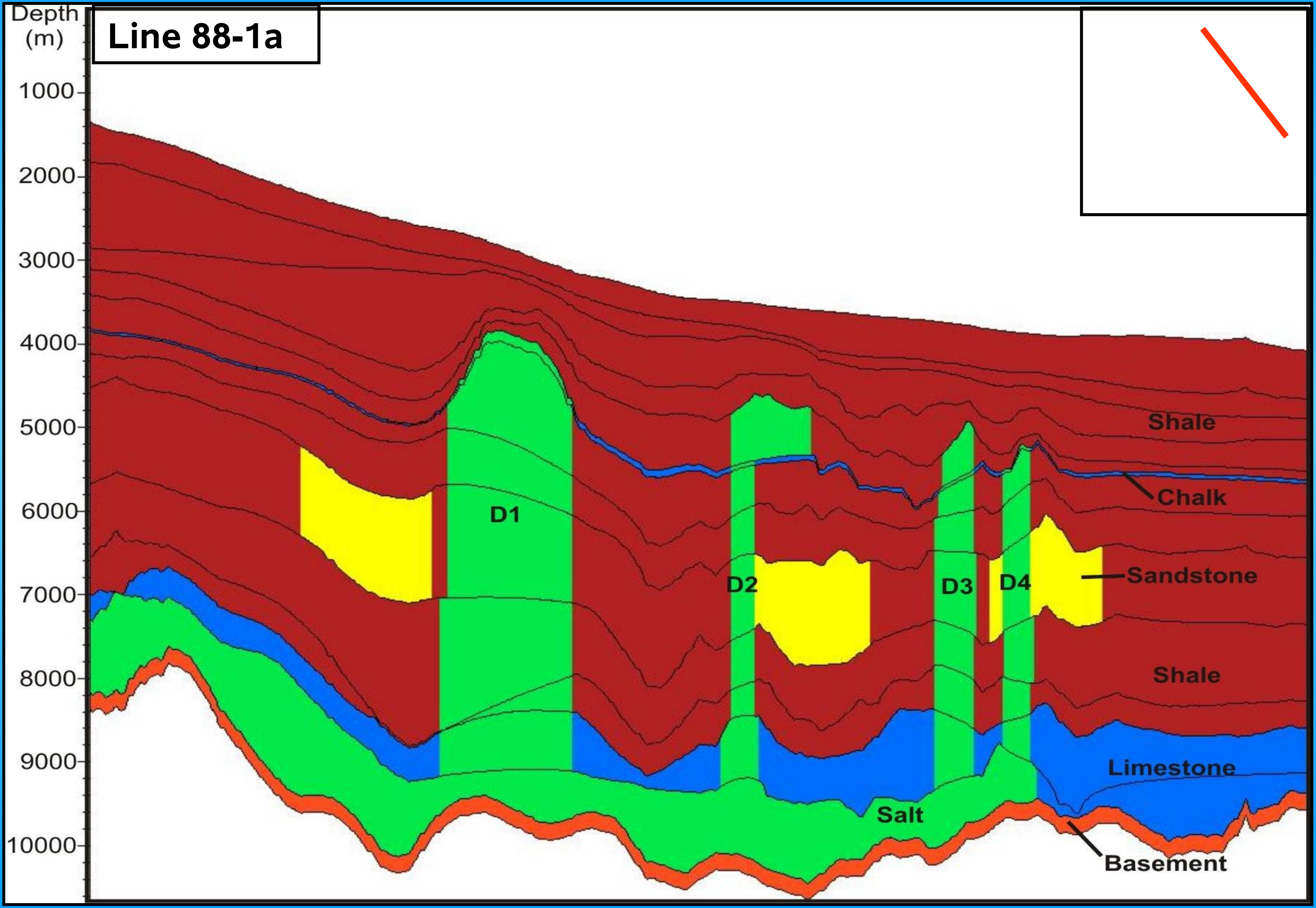
- Peak surface heat-flow of ~78 mW/m²



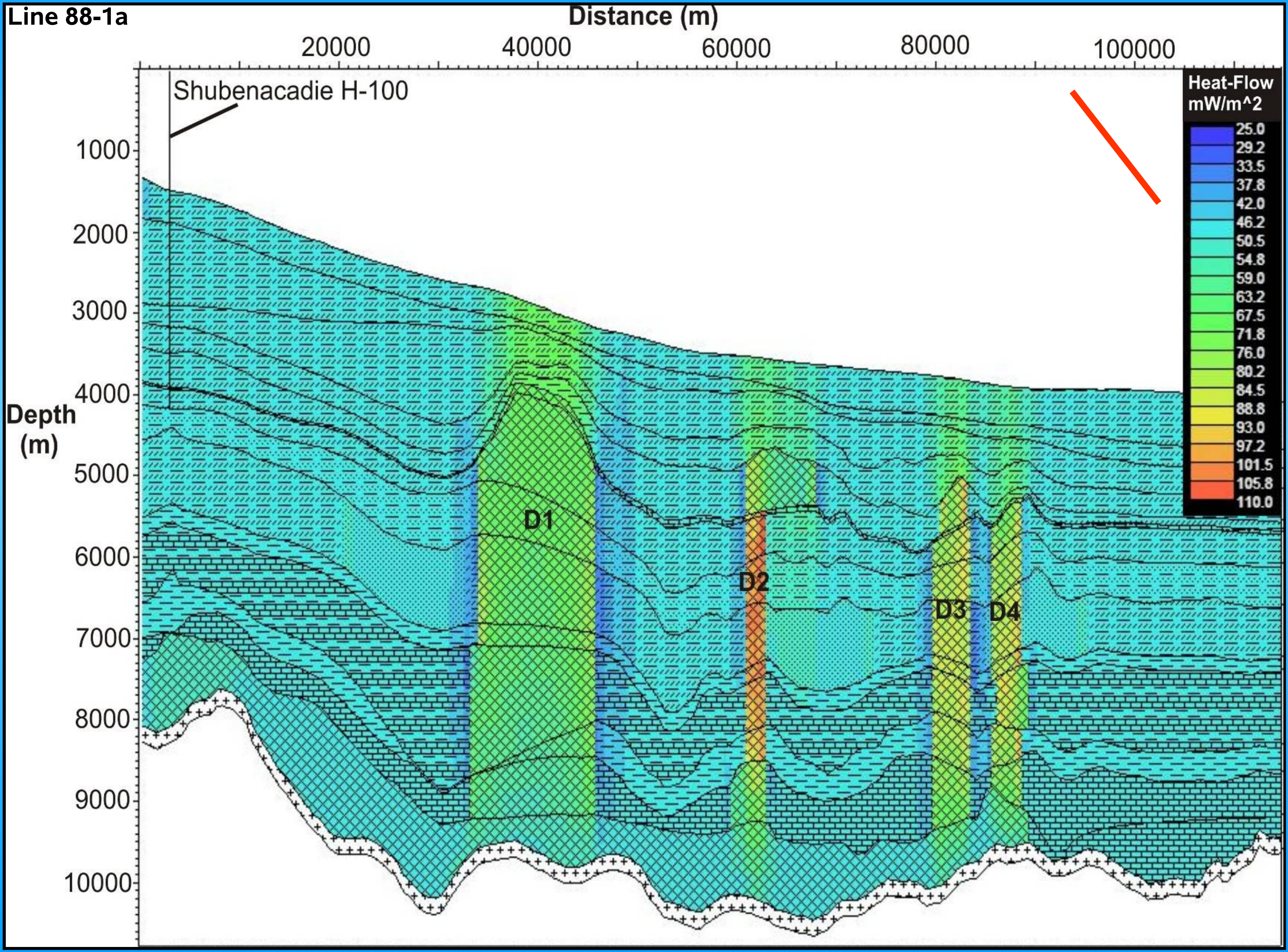


Surface view of Top Abenaki showing diapir location

General lithologies in line 88-1a

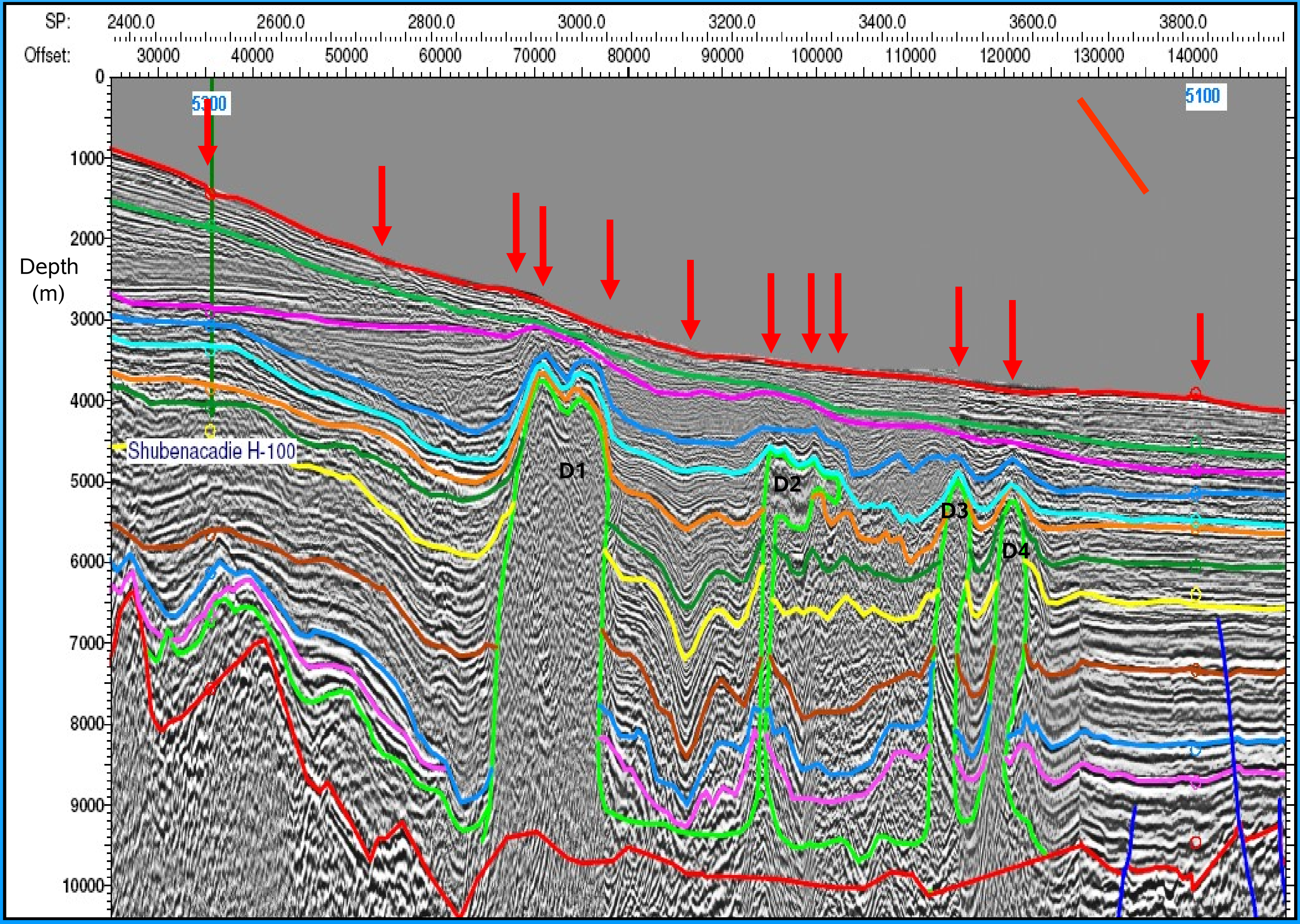


Heat-flow through line 88-1a

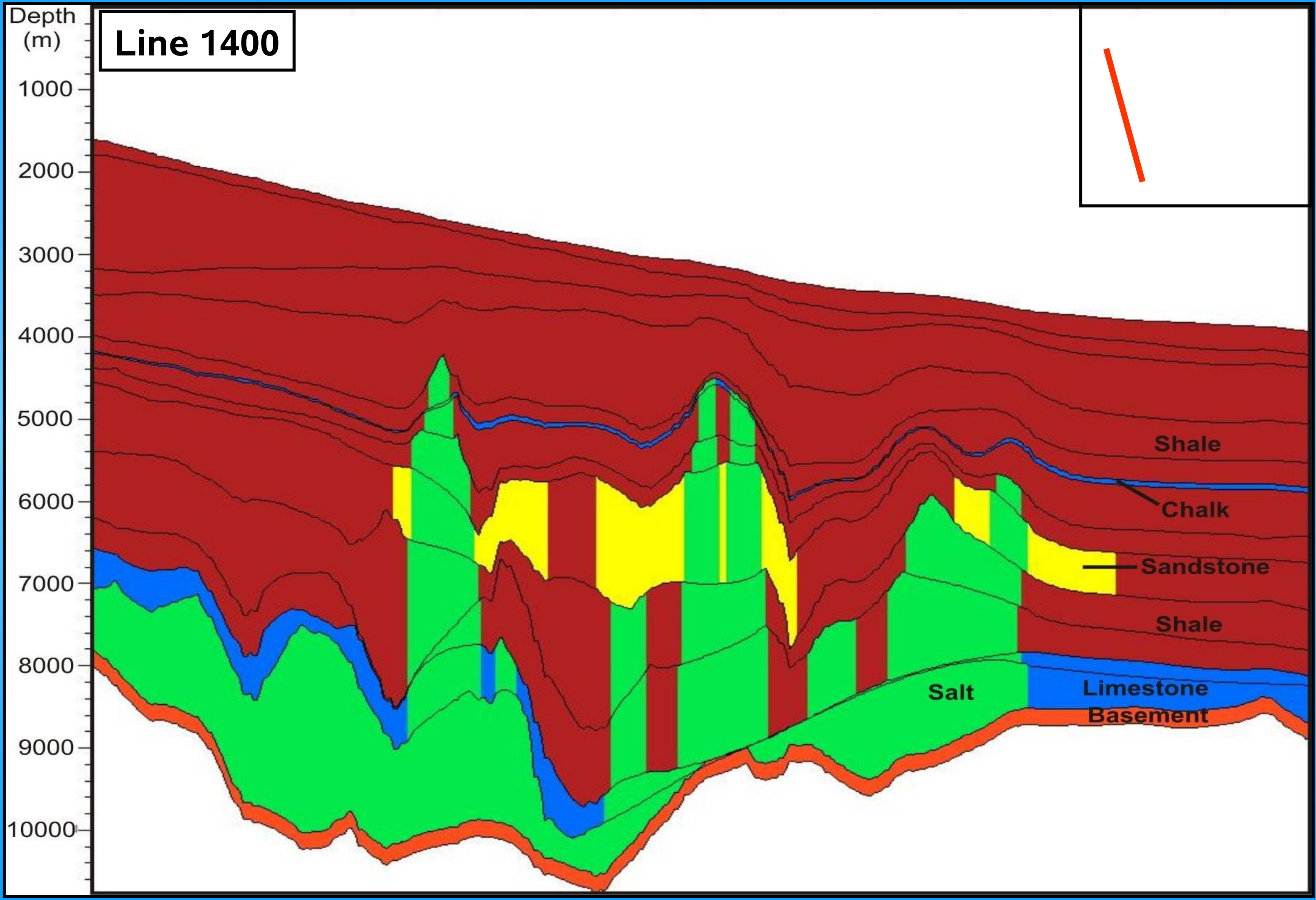


Locations for future heat-flow measurements to be taken along line 88-1a

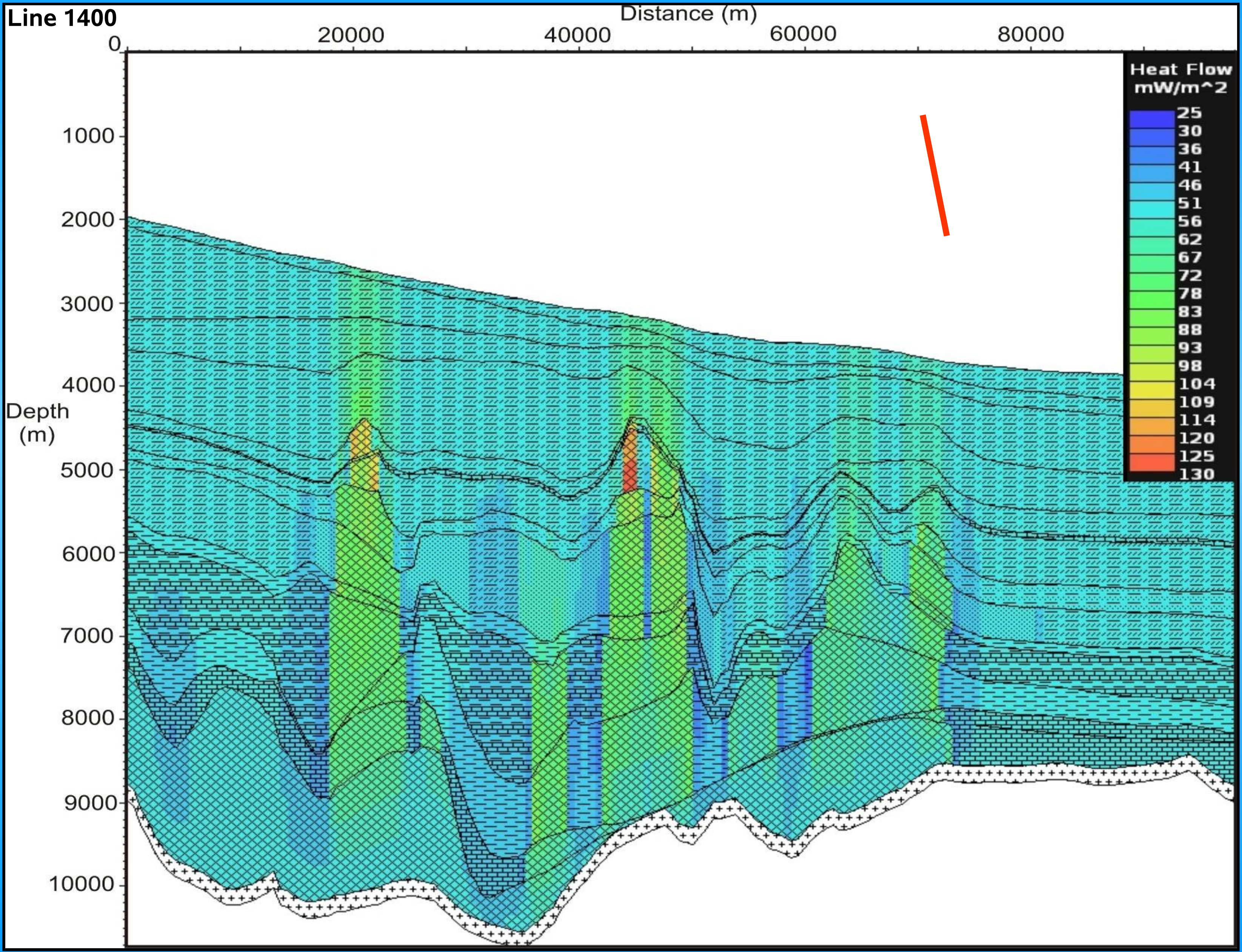
- Above largest salt diapirs
- Above salt tongue in D2
- In regions unaffected by salt diapirs



General lithologies in line 1400

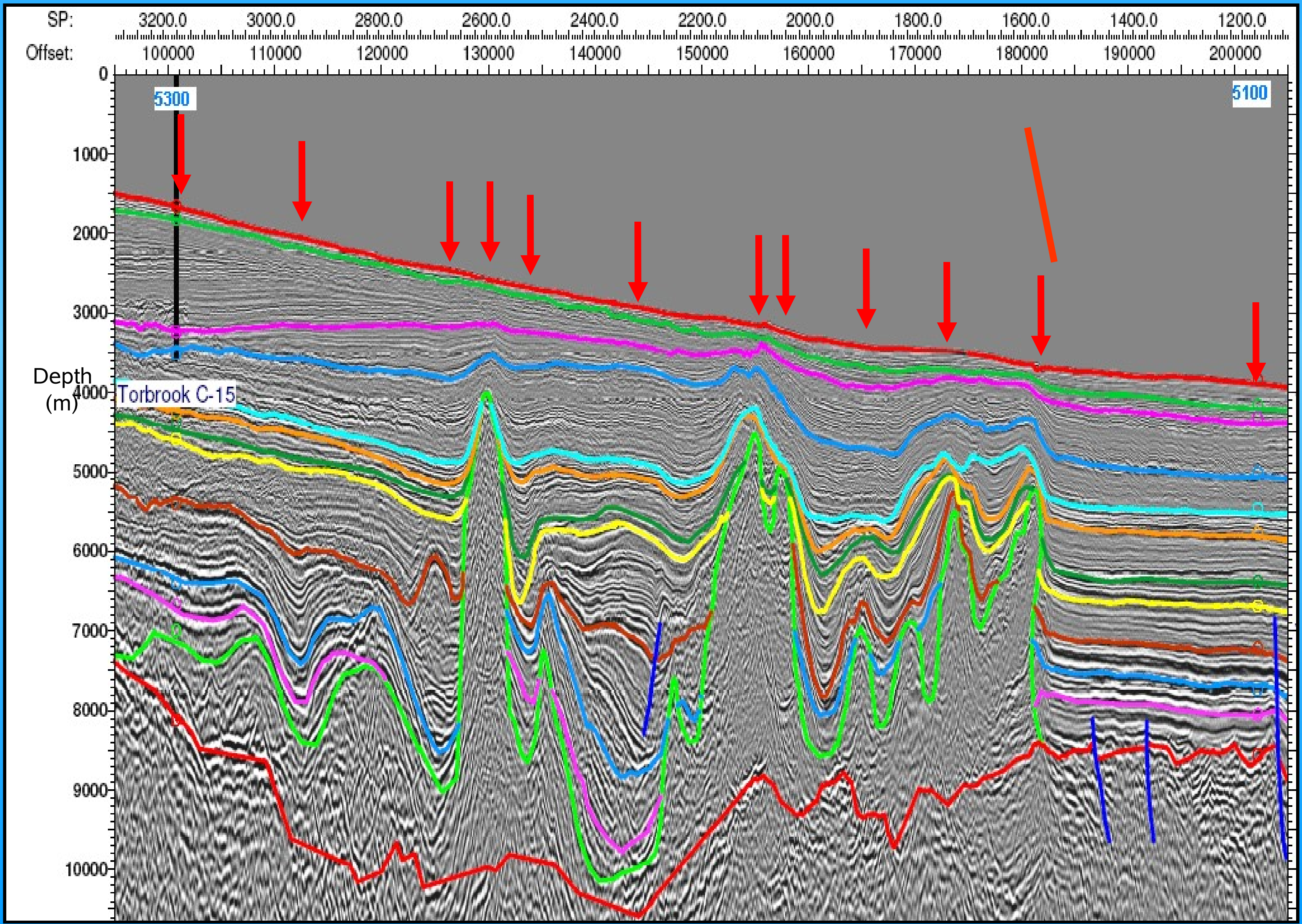


Heat-flow through line 1400

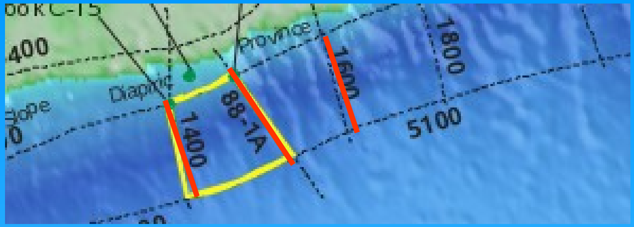


Locations for future heat-flow measurements to be taken along line 1400

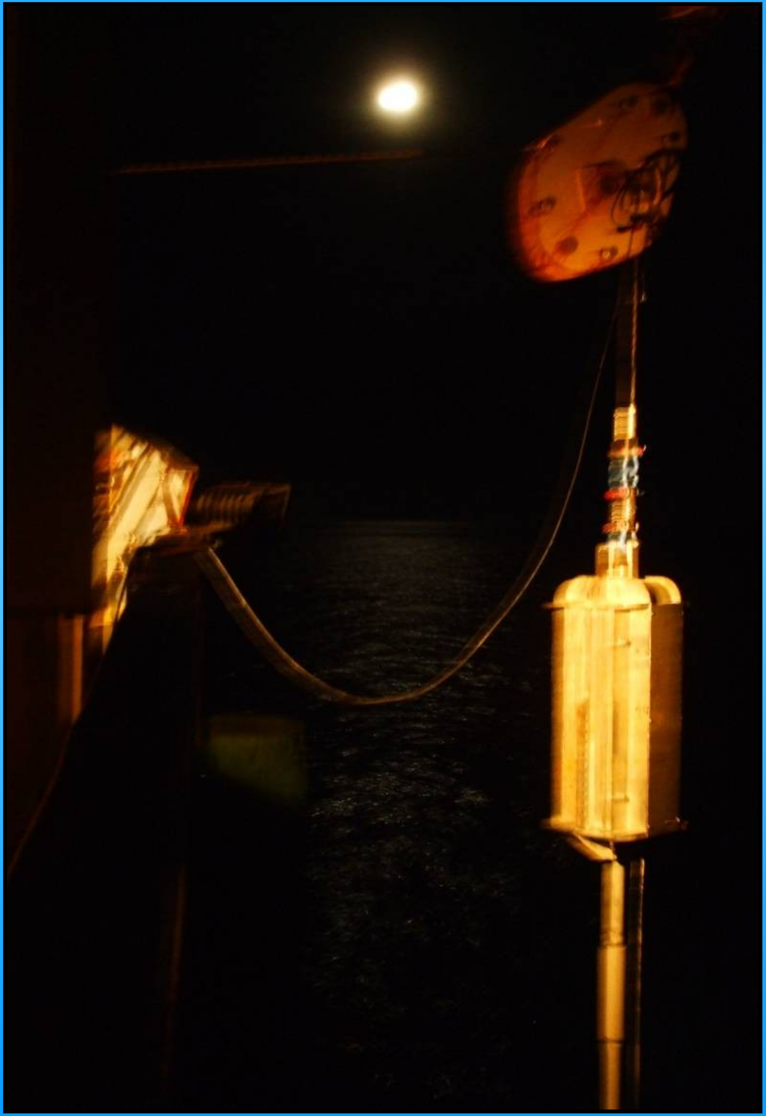
- Above largest salt diapirs
- Above smaller salt diapirs
- In regions unaffected by salt diapirs



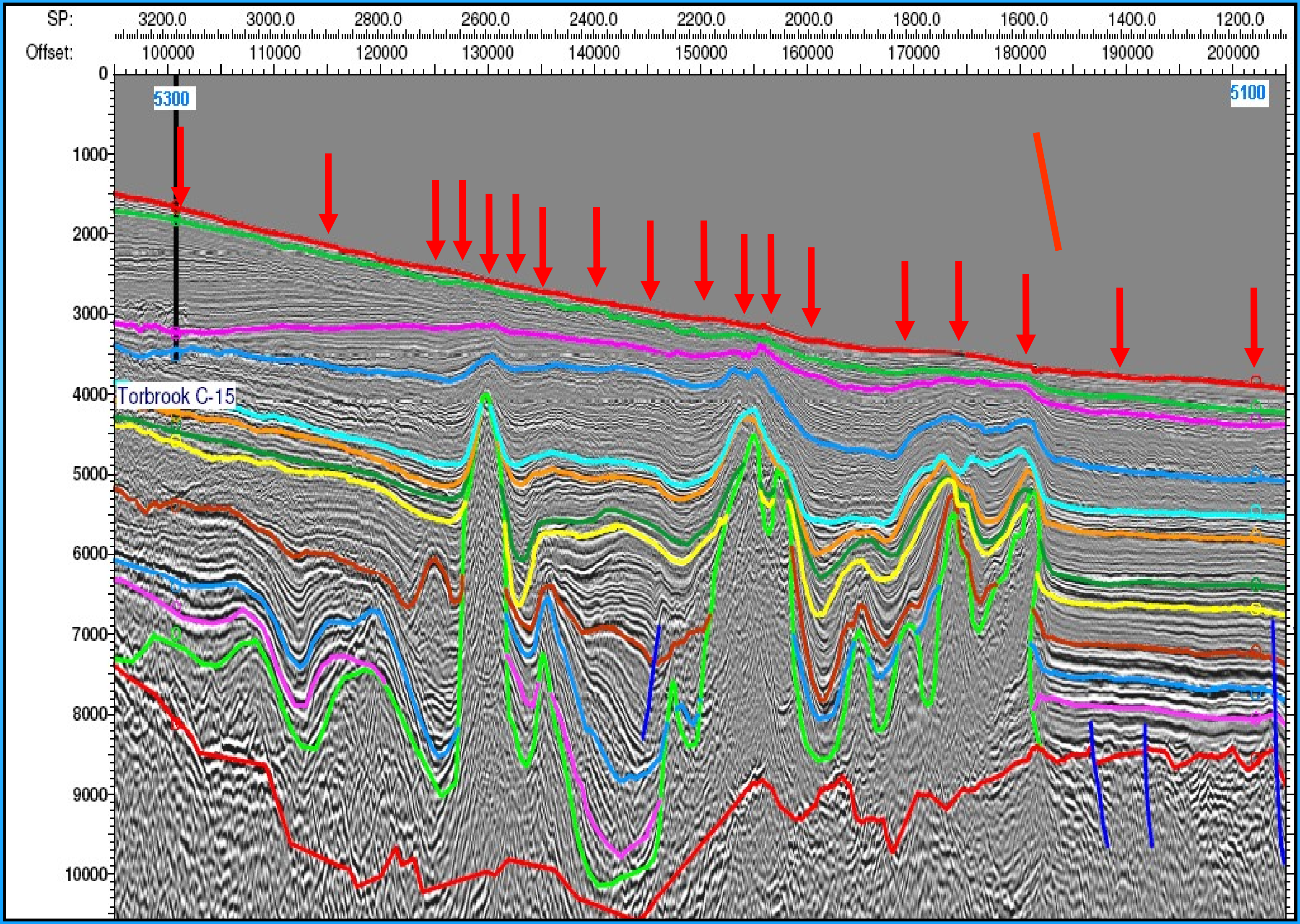
So We're Off to Sea!



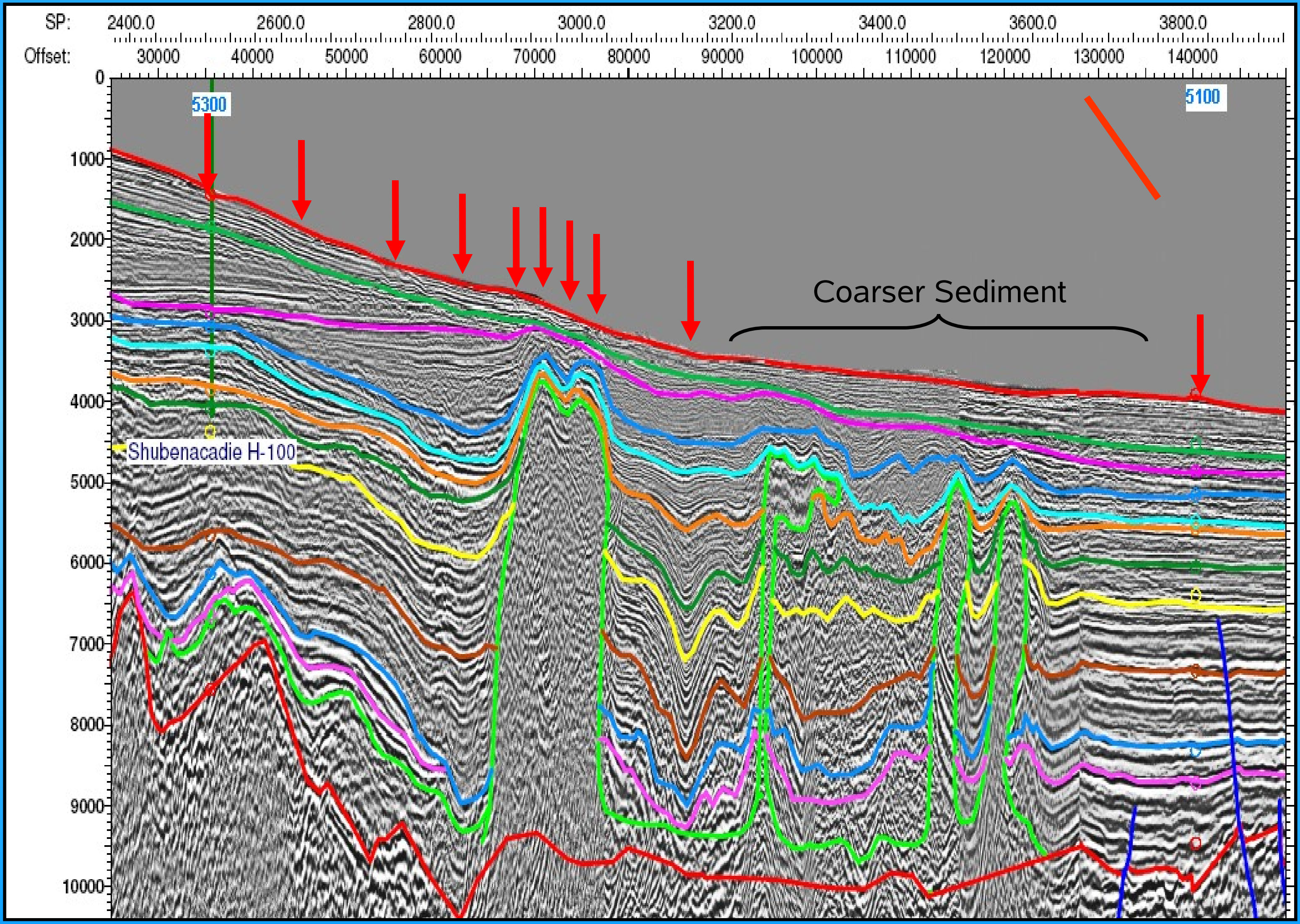
Who: Dr. Keith Louden and Co.
What: Heat-flow measurements!
When: July 17-25th, 2008
Where: Central Scotian Slope, Lines 1400, 1600 and 88-1a
Why: Improve our knowledge of heat-flow on the Scotian Slope
How: Dalhousie heat-flow probe and the CCGS Hudson



Locations of heat-flow measurements along line 1400



Locations of heat-flow measurements along line 88-1a



Conclusions

Heat-flow

- Increased heat-flow above salt diapirs
- Decreased heat-flow adjacent to salt diapirs
- Diapir width and height (proximity to seafloor) appear have direct effect on surface heat-flow
- Significant variations in heat-flow throughout the study area associated with locations of salt diapirs
- Highest surface heat-flow above diapir D1 on line 88-1a

Future Work

- Calibrate models with heat-flow measurements from July 2008 cruise
- Create model predicting heat-flow for more Eastern regions of the Scotian Slope in and around the Sable Subbasin (Phase II Area)
- Take heat-flow measurements from Phase II area in summer 2009 and calibrate model with these results
- Use final heat-flow models to interpret hydrocarbon maturation potential of the region and the effects of salt diapirs on maturation

Acknowledgments

- GX Technologies (NovaSPAN seismic survey)
- IES (PetroMod 4D modelling software)
- Dr. Hans Wielens
- Dr. Keith Louden
- Dr. Mladen Nedimovic

Questions

References

•Geissman, J. and Palmer, A.R., 1999. 1999 Geologic Time Scale. Geological Society of America Website: http://www.geosociety.org/science/timescale/timescl.htm

•Haq, B.U., Hardenbol, J., and Vail, P.R., 1987. Chronology of the fluctuating sea levels since the Triassic. *Science,* Vol. 235, p.1156-1167.

•Shimeld, J., and Wade, J., 2005. Seismostratigraphic Interpretation of the GX Technology NovaSPAN seismic survey, Nova Scotia Margin, Canada. *GX Technology publications*

Rift Analysis for the Jeanne d'Arc Basin

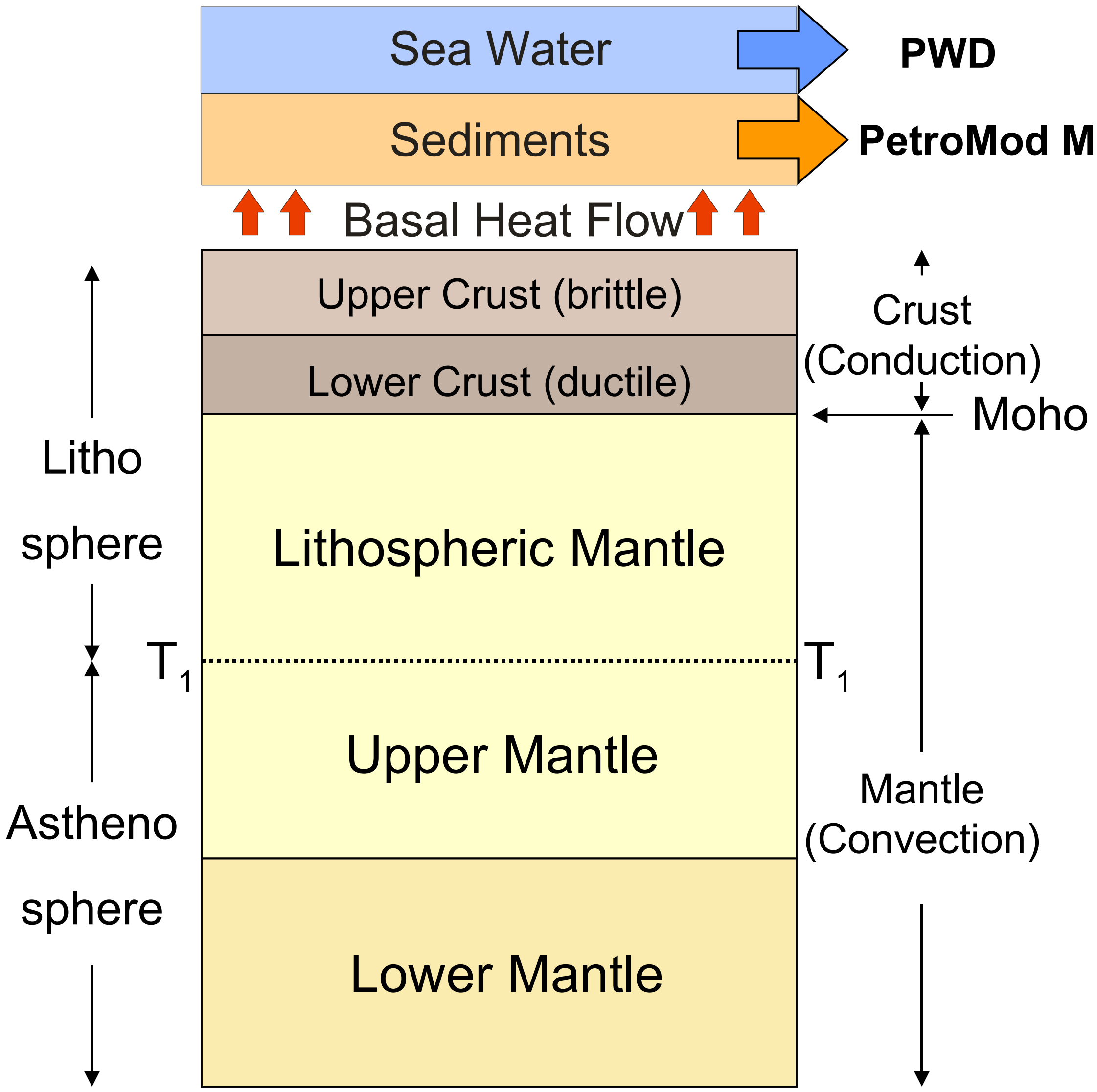
Using PetroMod® 1D

Halifax, August 2008

Friedemann Baur
(Geologist)

Theory of Rift models

Definitions



$\rho_{sw} \approx 1.06$ g/cm^3

$\rho_s \approx 2.2$ g/cm^3

$\rho_c \approx 2.8$ g/cm^3

$\rho_m \approx 3.3$ g/cm^3

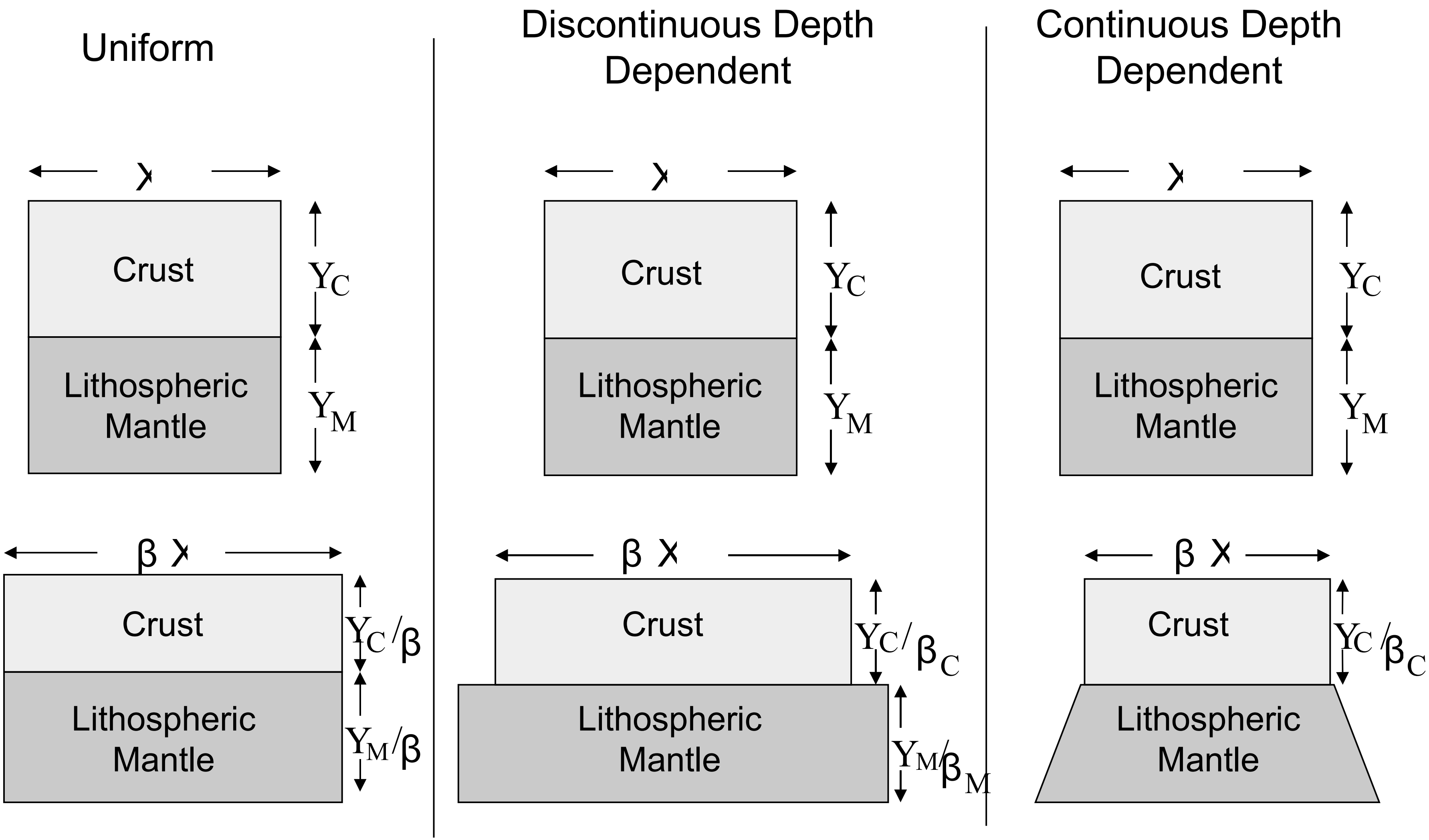
$T_1 = 3/4 T_M \approx 1333$°C

= first liquid material

T_M = pyrolite melting temp

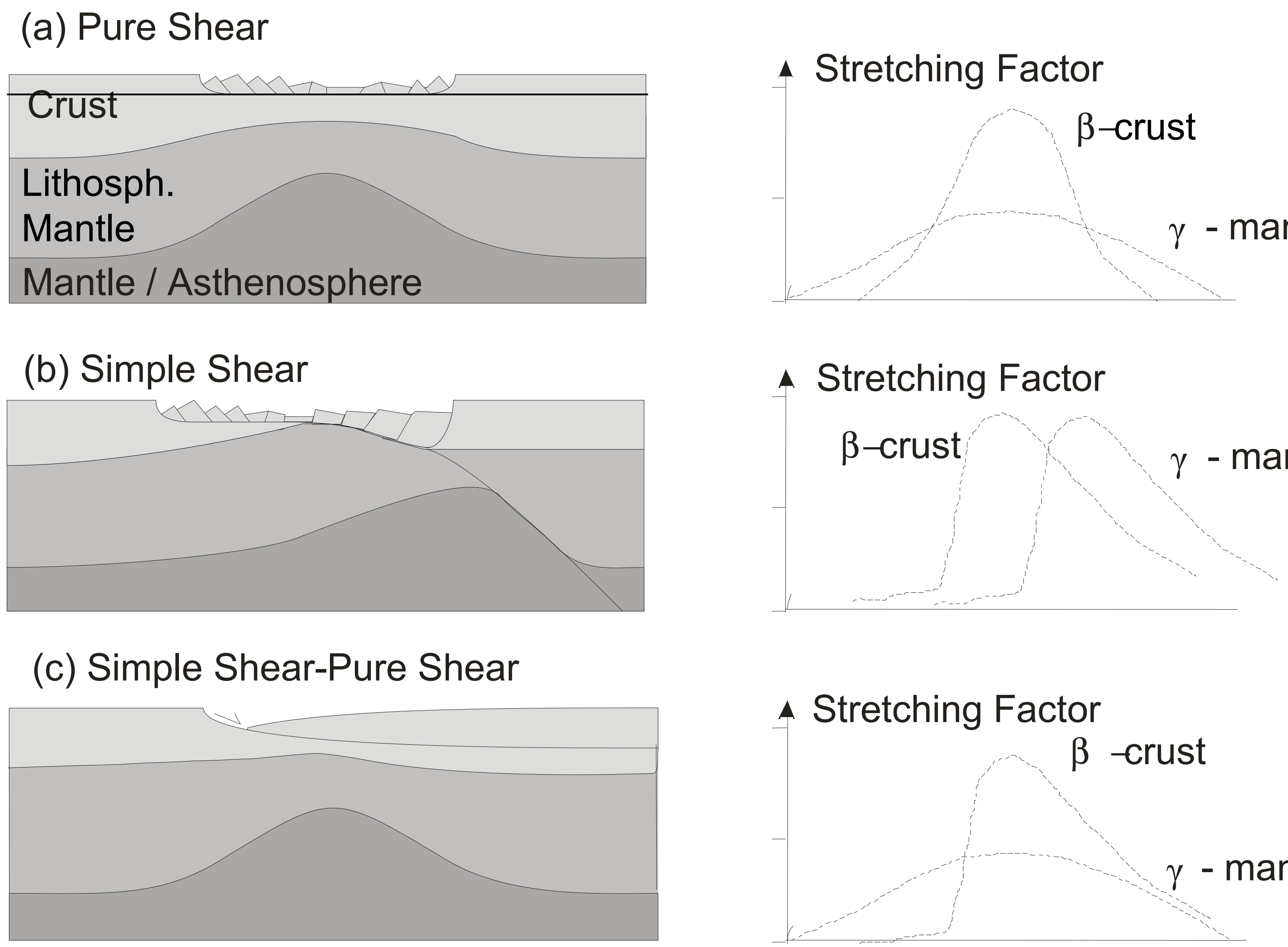
Theory of Rift models

Different Stretching Models



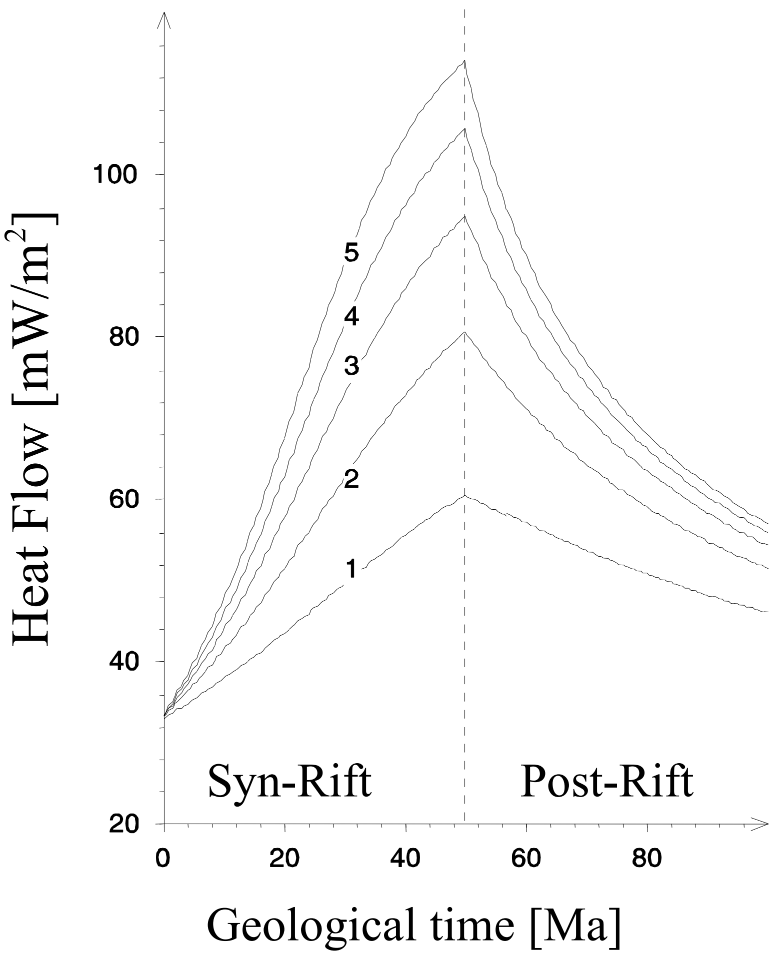
Theory of Rift models

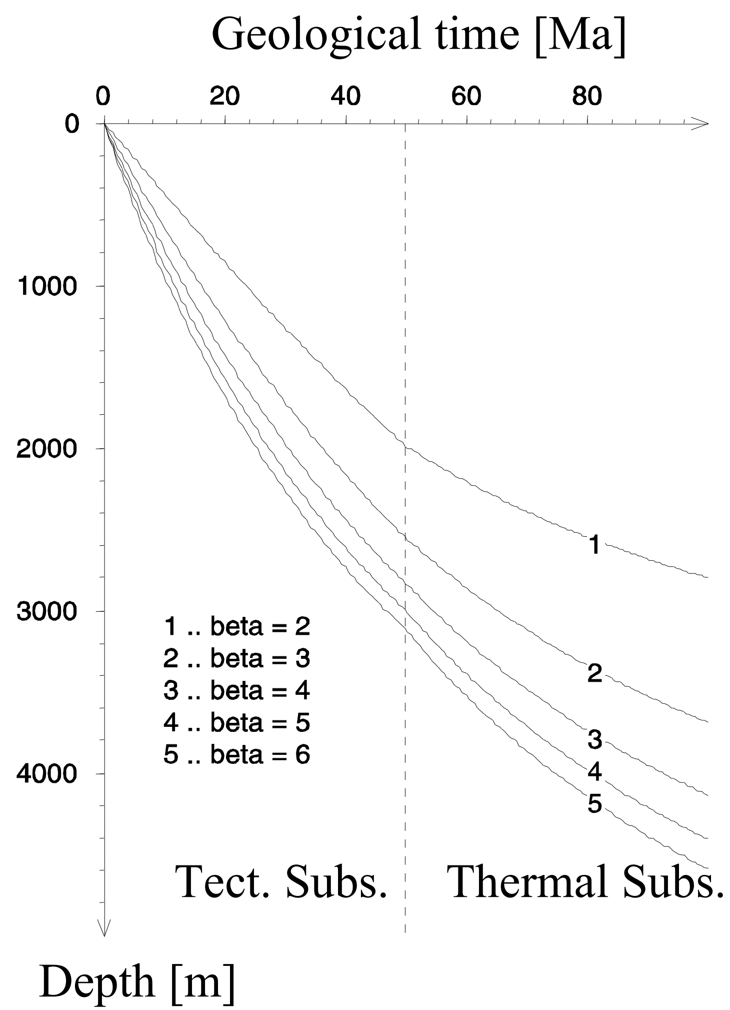
Different Crustal Models



Theory of Rift models

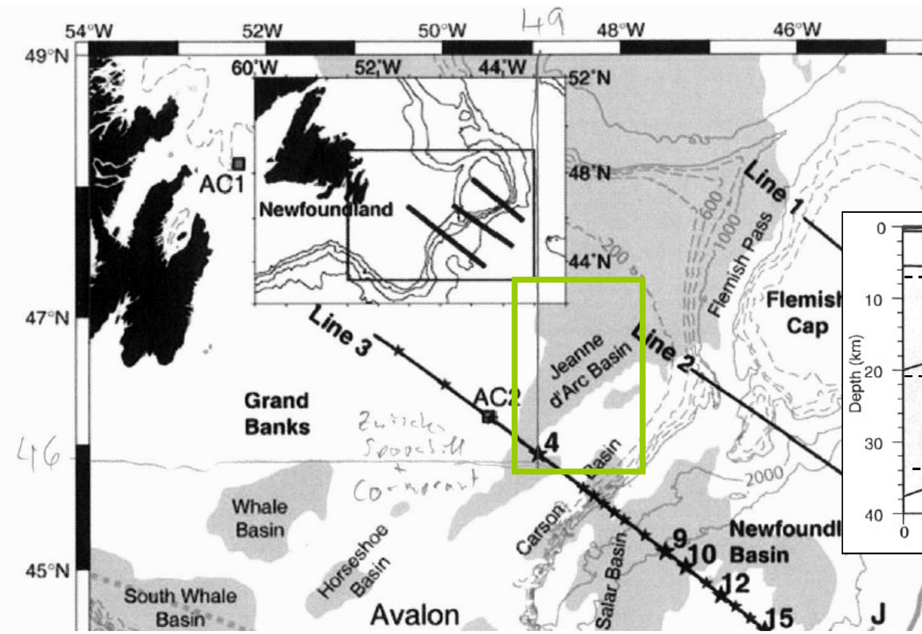
Heat Flow & Subsidence

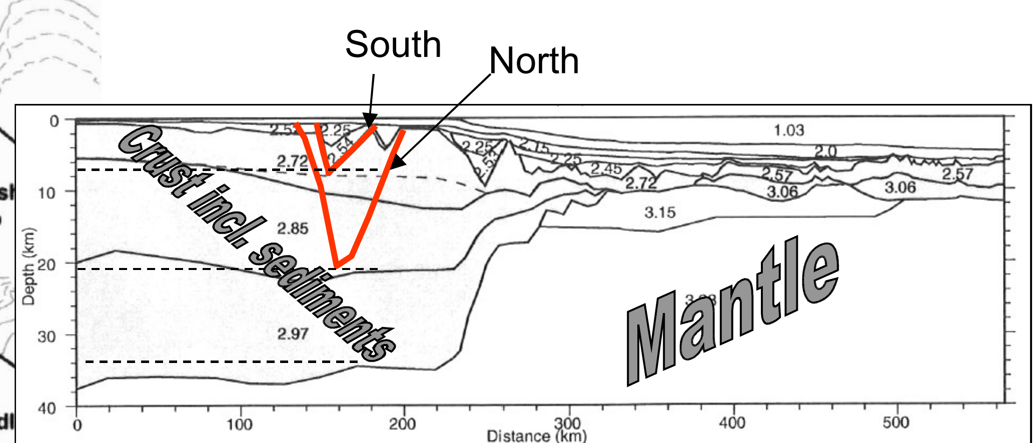




Present width / Initial width = Stretching Factor

Crust Thickness

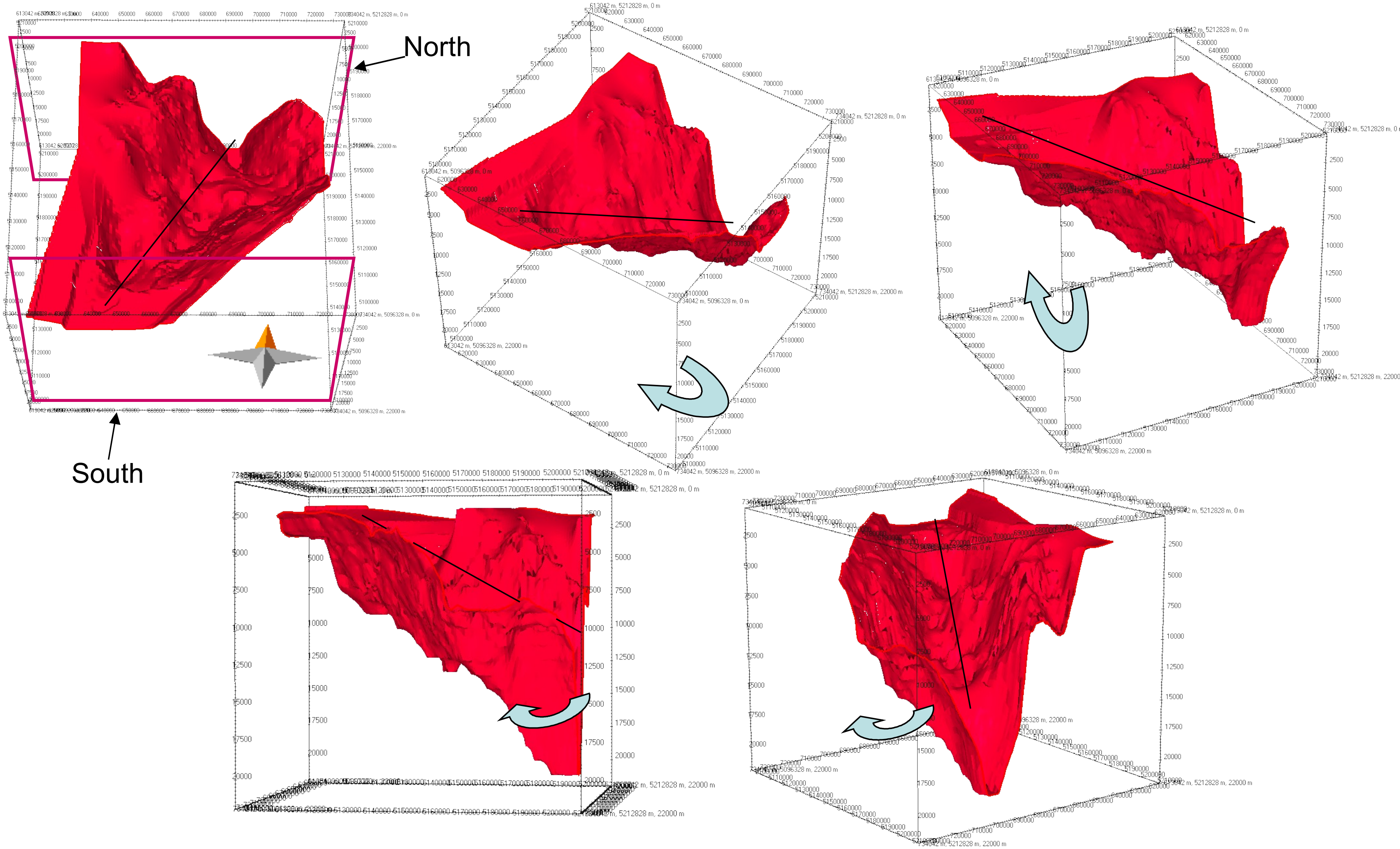




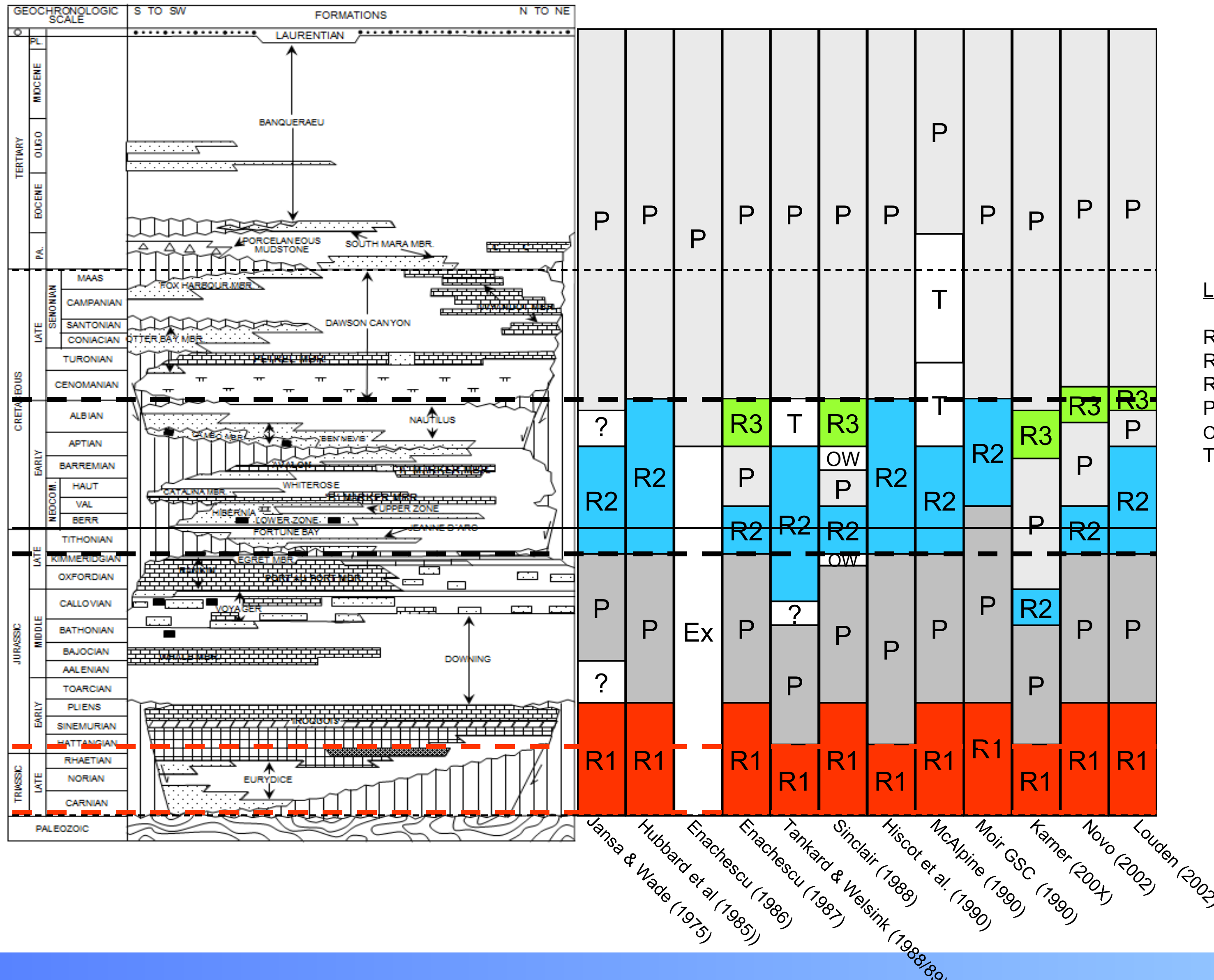
Present-day crustal thickness ≈ 35-36 km

K.W. Helen Lau et al., 2006: Crustal structure across the Grand Banks…” Geophys. J. Int. (2006) 167, 127-156

Top Basement



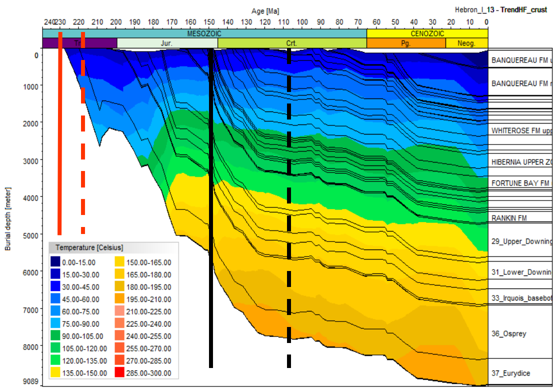
Rift Phases



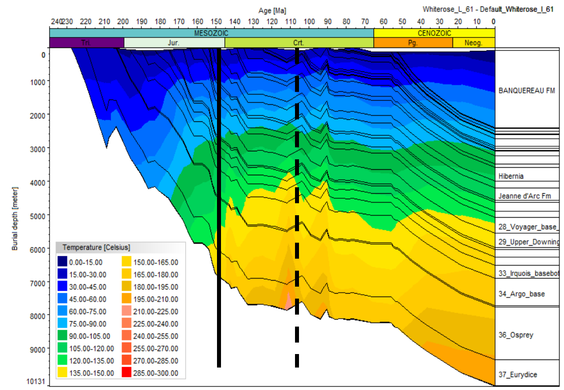
LEGEND

R1 = Rift 1
R2 = Rift 2
R3 = Rift 3
P = Passive Margin
OW = Onset Warp
T = Transition

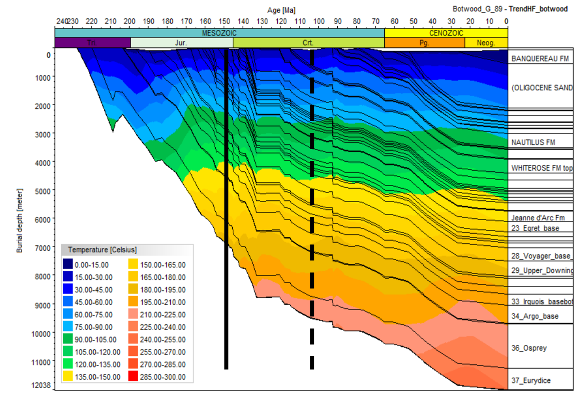
Burial Histories



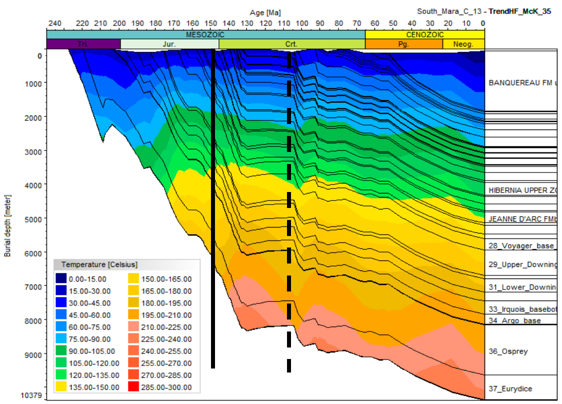
Hebron I 13



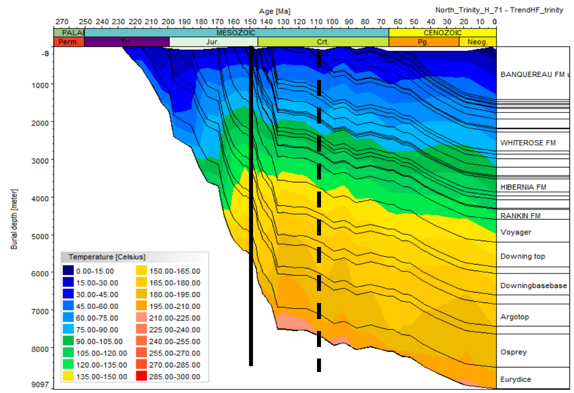
Whiterose L 61



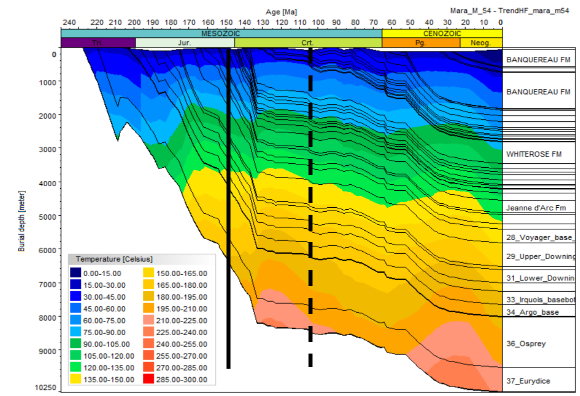
Botwood G 89



South Mara C 13

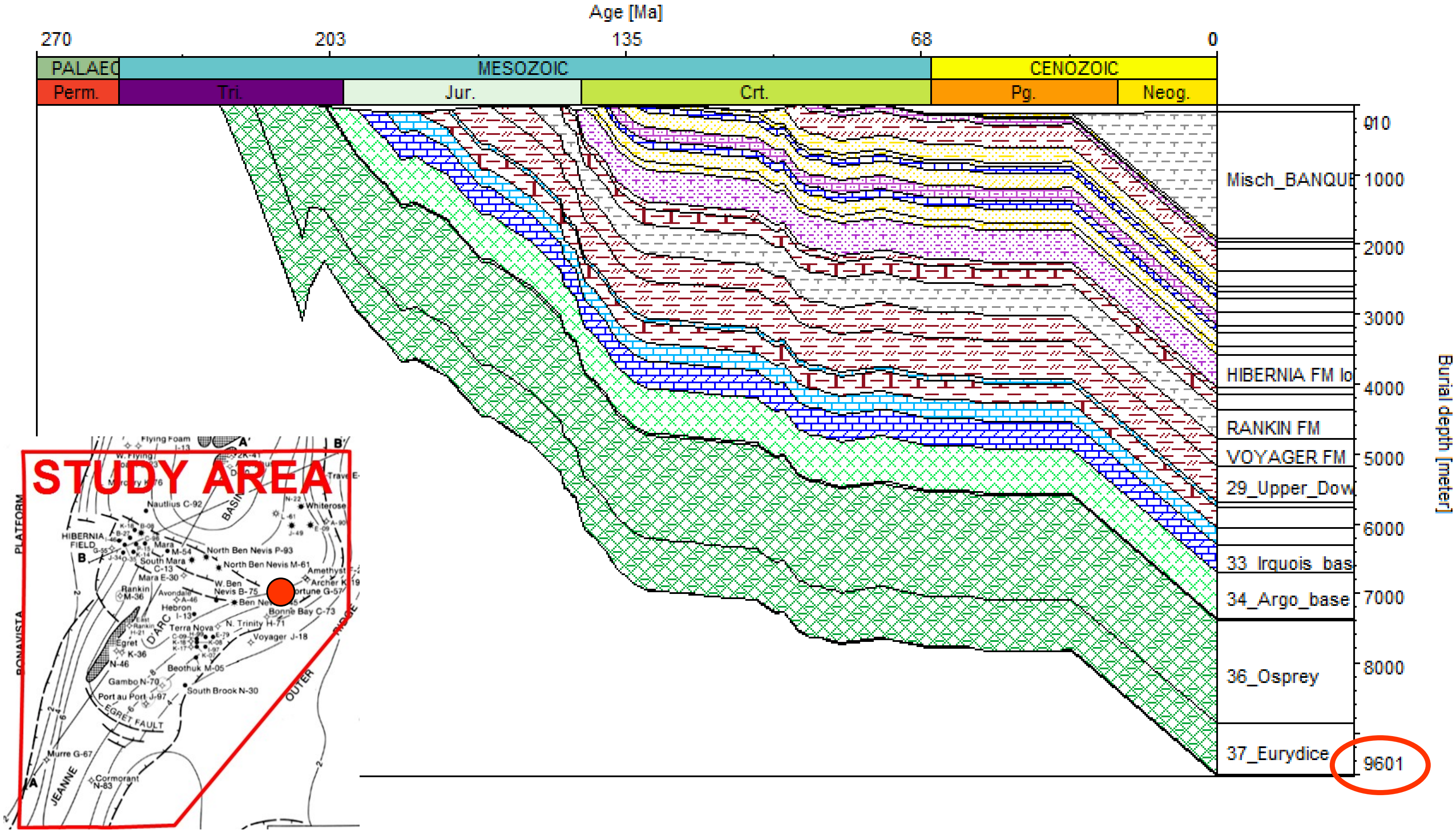


North Trinity H 71



Mara M 54

Fortune G-57


Age [Ma]
270
203
135
68
0
PALAEO
MESOZOIC
CENOZOIC
Perm.
Tri.
Jur.
Crt.
Pg.
Neog.
Misch_BANQUE
HIBERNIA FM lo
RANKIN FM
VOYAGER FM
29_Upper_Dow
33_Irquois_bas
34_Argo_base
36_Osprey
37_Eurydice
010
1000
2000
3000
4000
5000
6000
7000
8000
9601
Burial depth [meter]
STUDY AREA
HIBERNIA FIELD
North Ben Nevis P-93
North Ben Nevis M-61
Nautilus C-92
Whiterose
Amethyst
Archer
Fortune G-57
Bonne Bay C-73
N. Trinity H-71
Voyager J-18
Terra Nova
Hebron
Avondale
Rankin M-36
Mara E-30
South Mara C-13
Beothuk M-05
South Brook N-30
Gambo N-70
Port au Port J-97
EGRET FAULT
Egret K-36
Murre G-67
Cormorant N-83
JEANNE
BONAVISTA PLATFORM
OUTER RIDGE

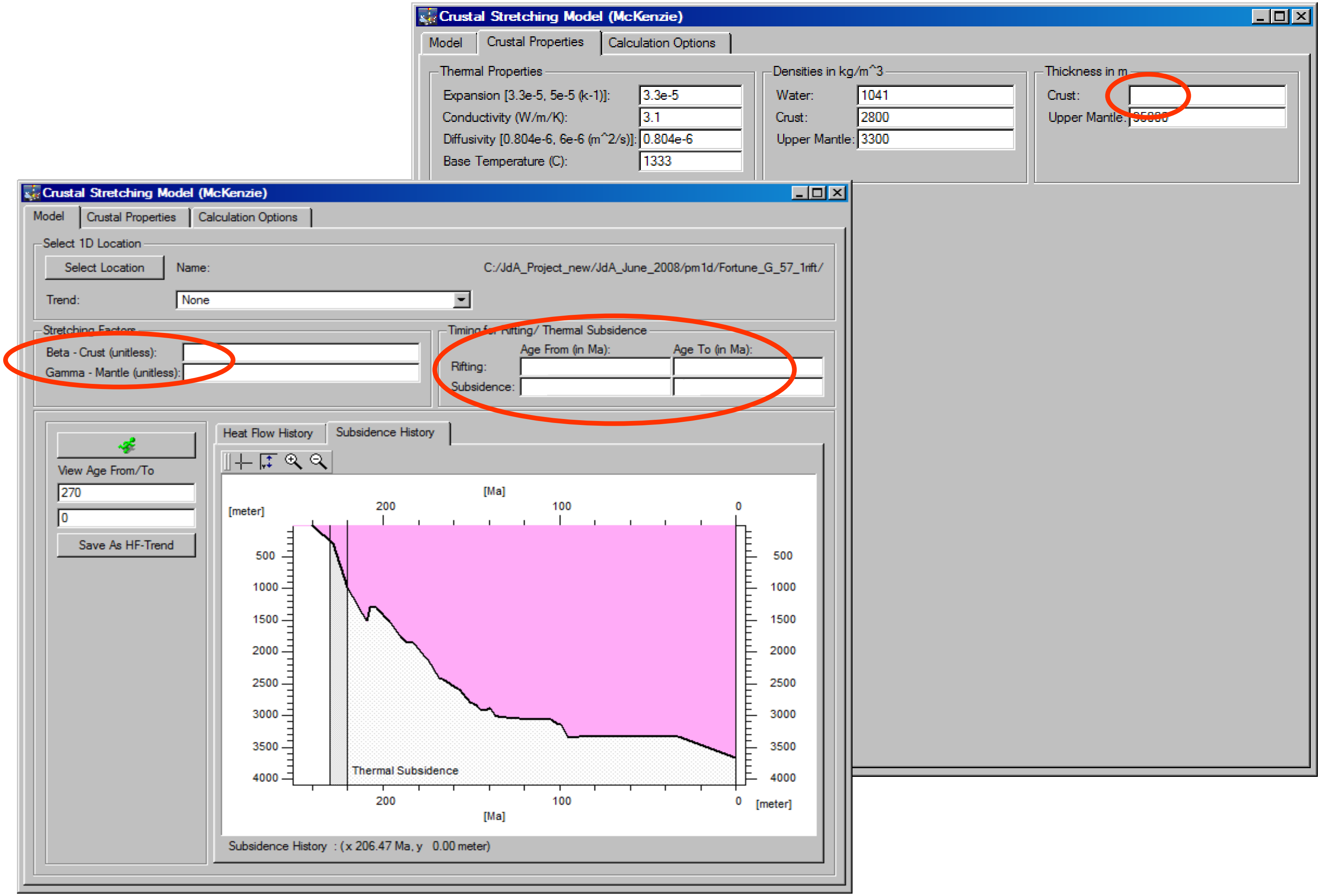
Collected Data

Fortune G-57:
Sediment thickness = 9.6 km
Crust thickness now ≈ 35-36 km
Rift from 230 to 220 Ma
Thermal Subsidence from 220 to 0 Ma

>> find stretching factors, which fits to all given parameters !!!

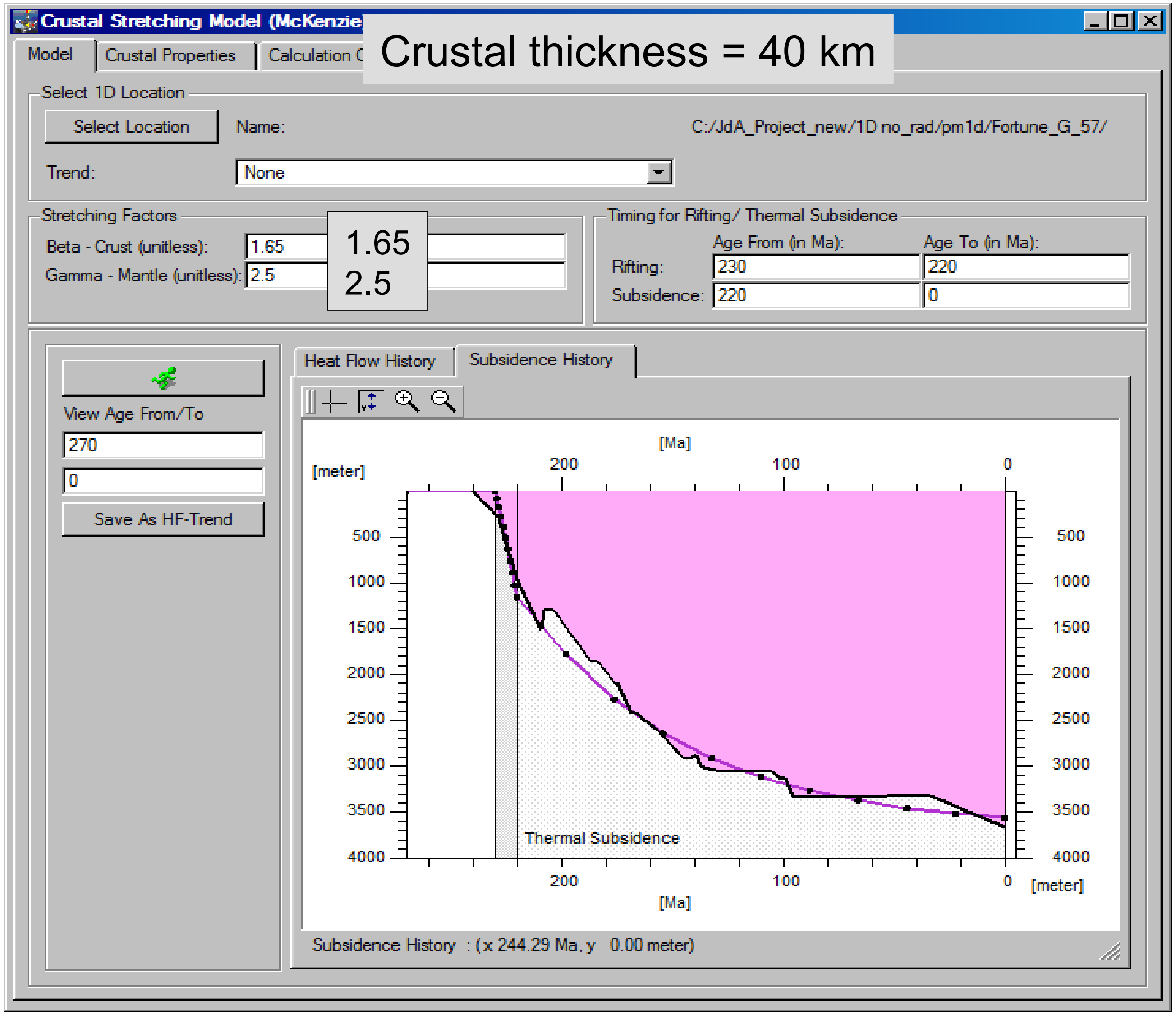
>> find initial Crustal thickness (by trial and error) !!!

Data Input



Crustal Stretching Model (McKenzie)
Model
Crustal Properties
Calculation Options
Thermal Properties
Expansion [3.3e-5, 5e-5 (k-1)]: 3.3e-5
Conductivity (W/m/K): 3.1
Diffusivity [0.804e-6, 6e-6 (m^2/s)]: 0.804e-6
Base Temperature (C): 1333
Densities in kg/m^3
Water: 1041
Crust: 2800
Upper Mantle: 3300
Thickness in m
Crust:
Upper Mantle:
Crustal Stretching Model (McKenzie)
Model
Crustal Properties
Calculation Options
Select 1D Location
Select Location
Name:
C:/JdA_Project_new/JdA_June_2008/pm1d/Fortune_G_57_1rift/
Trend:
None
Beta - Crust (unitless):
Gamma - Mantle (unitless):
Age From (in Ma):
Age To (in Ma):
Rifting:
Subsidence:
View Age From/To
270
0
Save As HF-Trend
Heat Flow History
Subsidence History
[Ma]
[meter]
200
100
0
500
1000
1500
2000
2500
3000
3500
4000
Thermal Subsidence
Subsidence History : (x 206.47 Ma, y 0.00 meter)

Example


Crustal Stretching Model (McKenzie
Crustal thickness = 40 km
Model
Crustal Properties
Calculation C
Select 1D Location
Select Location
Name:
C:/JdA_Project_new/1D no_rad/pm1d/Fortune_G_57/
Trend:
None
Stretching Factors
Beta - Crust (unitless): 1.65
Gamma - Mantle (unitless): 2.5
1.65
2.5
Timing for Rifting/ Thermal Subsidence
Age From (in Ma):
Age To (in Ma):
Rifting: 230 220
Subsidence: 220 0
View Age From/To
270
0
Save As HF-Trend
Heat Flow History
Subsidence History
[Ma]
[meter]
200
100
0
500
1000
1500
2000
2500
3000
3500
4000
Thermal Subsidence
Subsidence History : (x 244.29 Ma, y 0.00 meter)

Check Correctness

<u>Try 40 km</u>

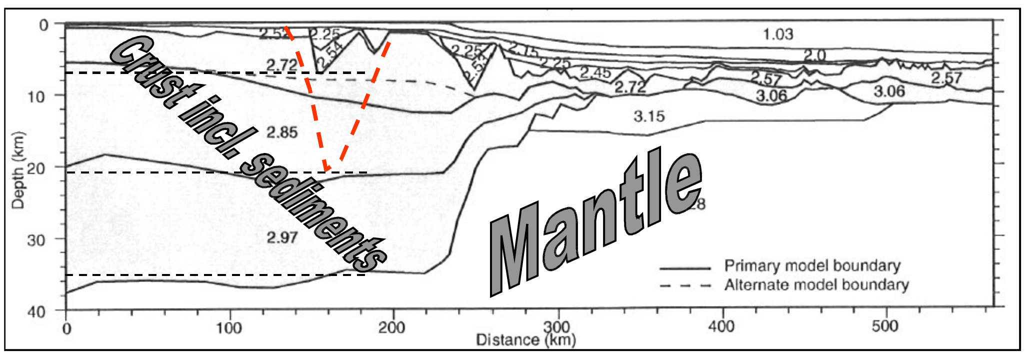
40 km / 1.65 = 24.24 km (thinned present-day crust)

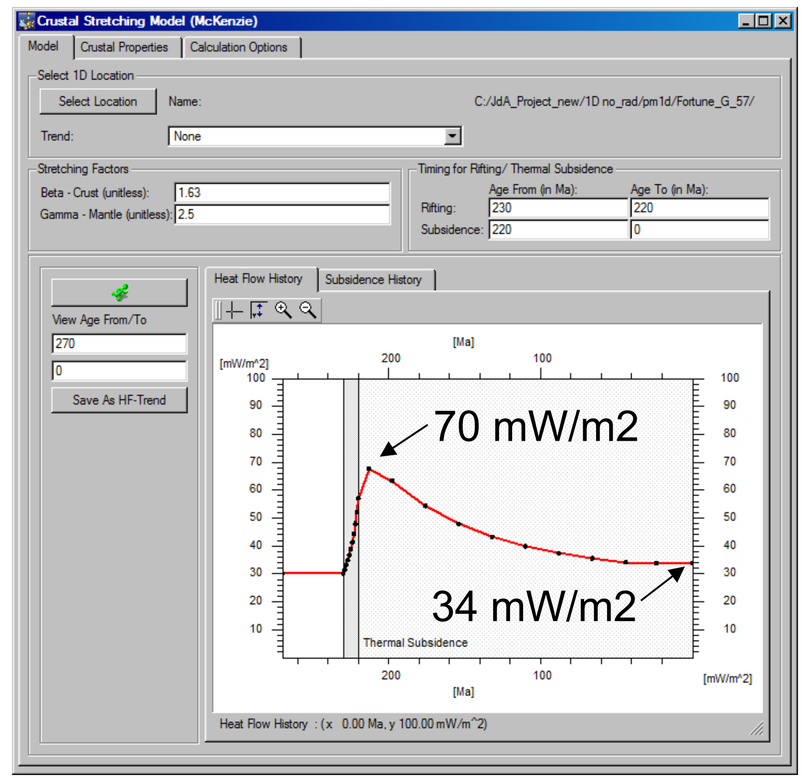
24.24 km crust + 9.6 km sediments = 33.84 km crust incl. sediments >> too low !

Try 42 km for the initial crustal thickness and adjust the tectonic subsidence again

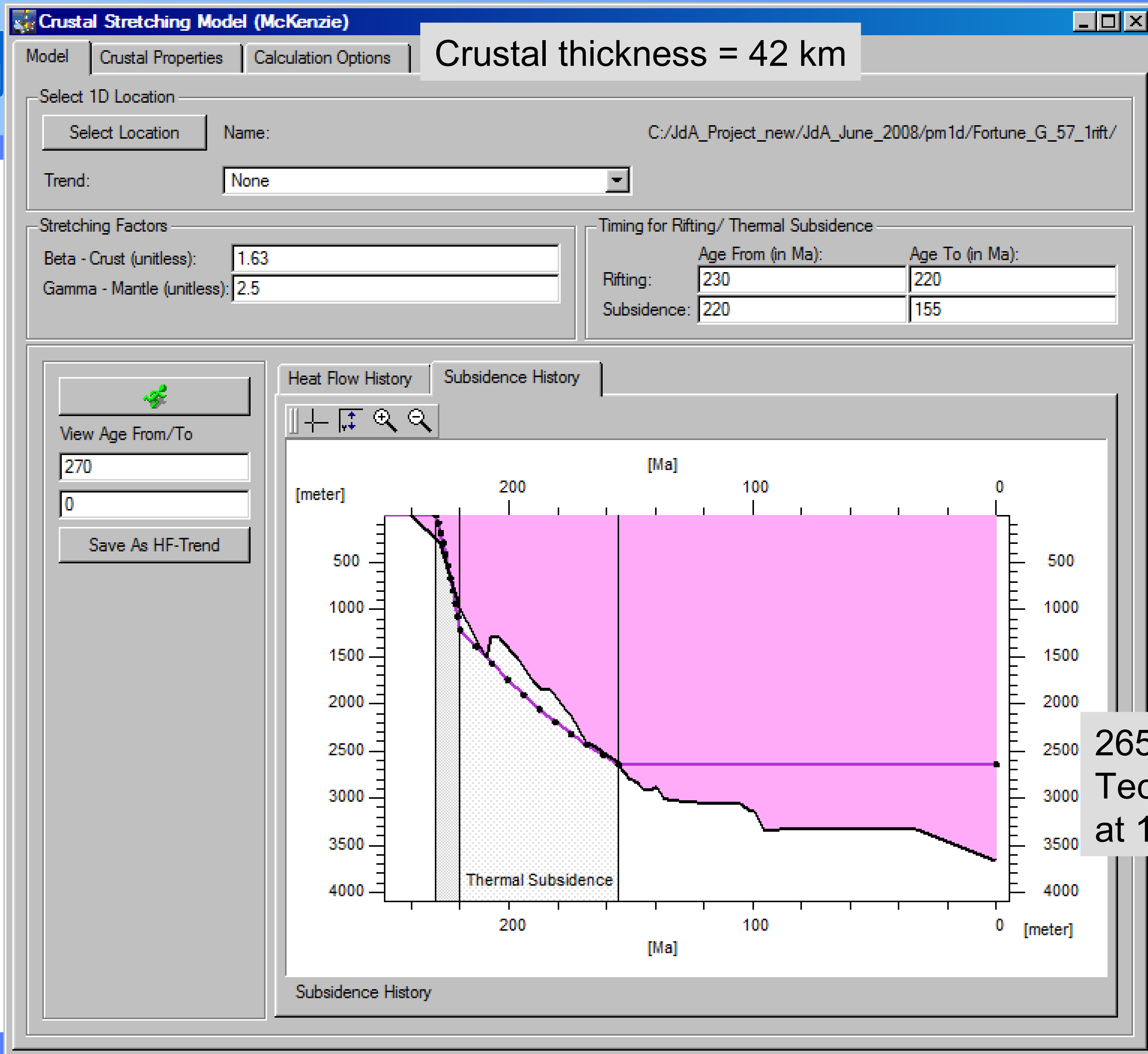
42 / 1.63 = 25.76

25.76 + 9.6 = 35.36 >> good !



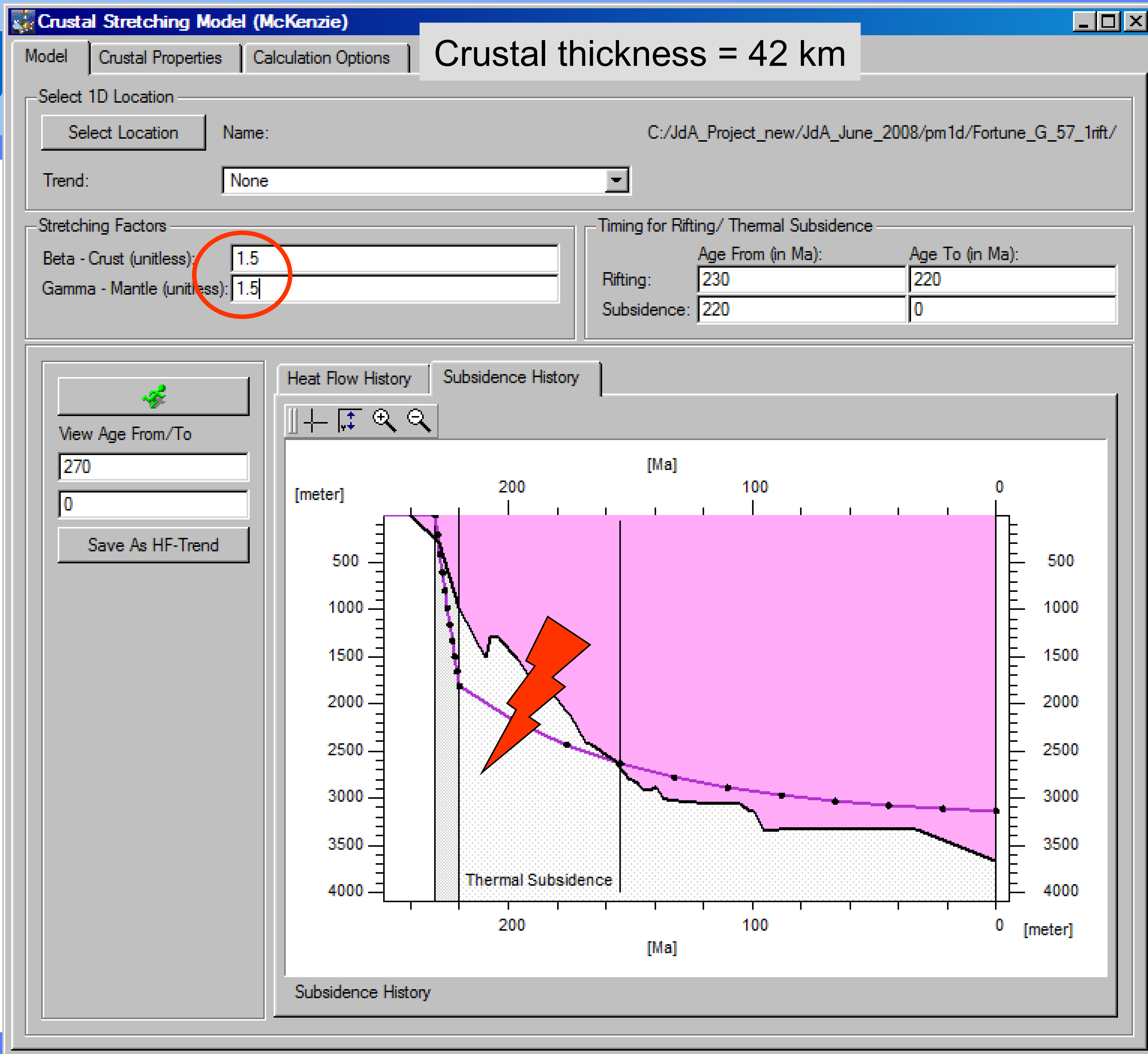


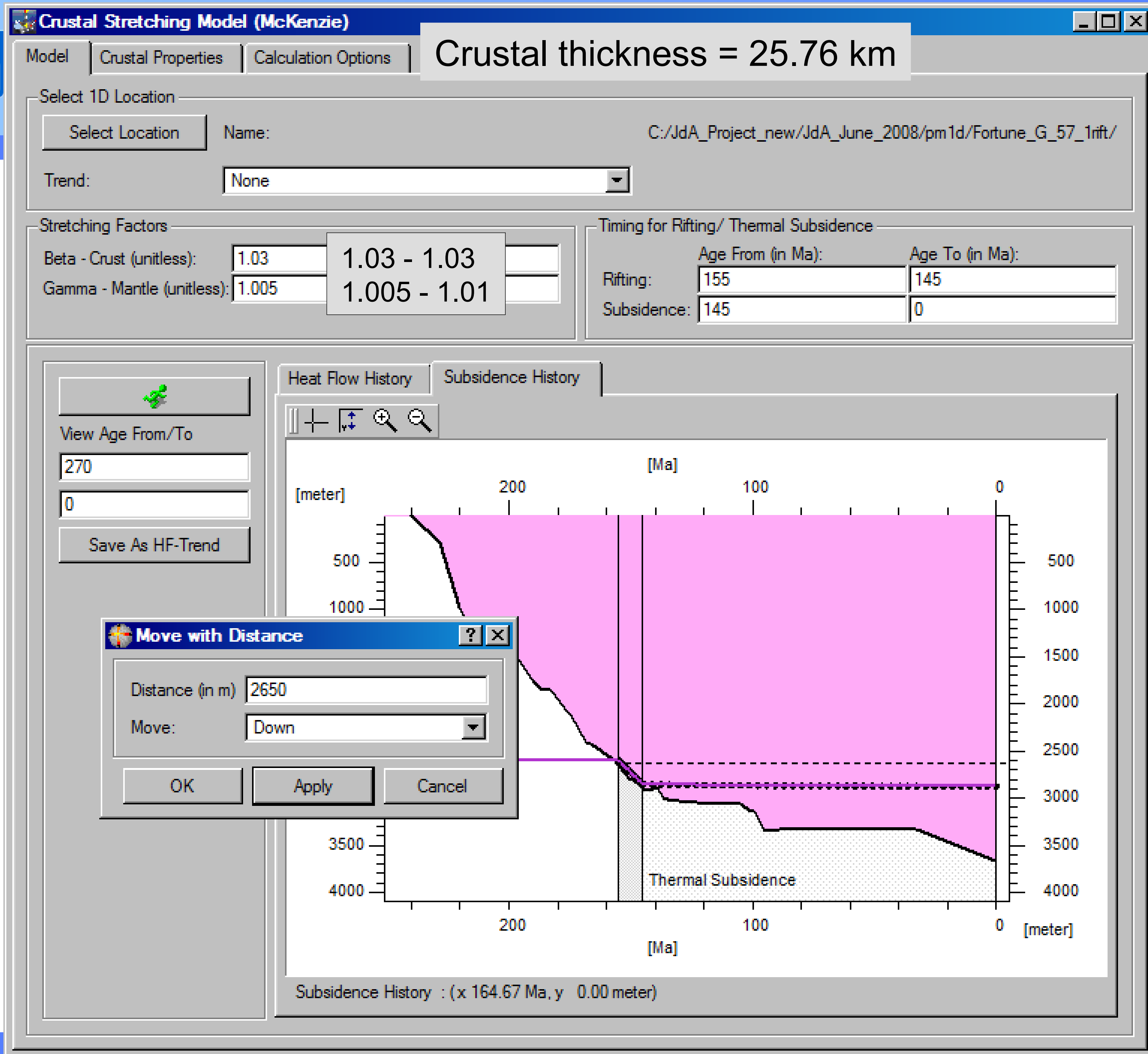
Crustal thickness = 42 km

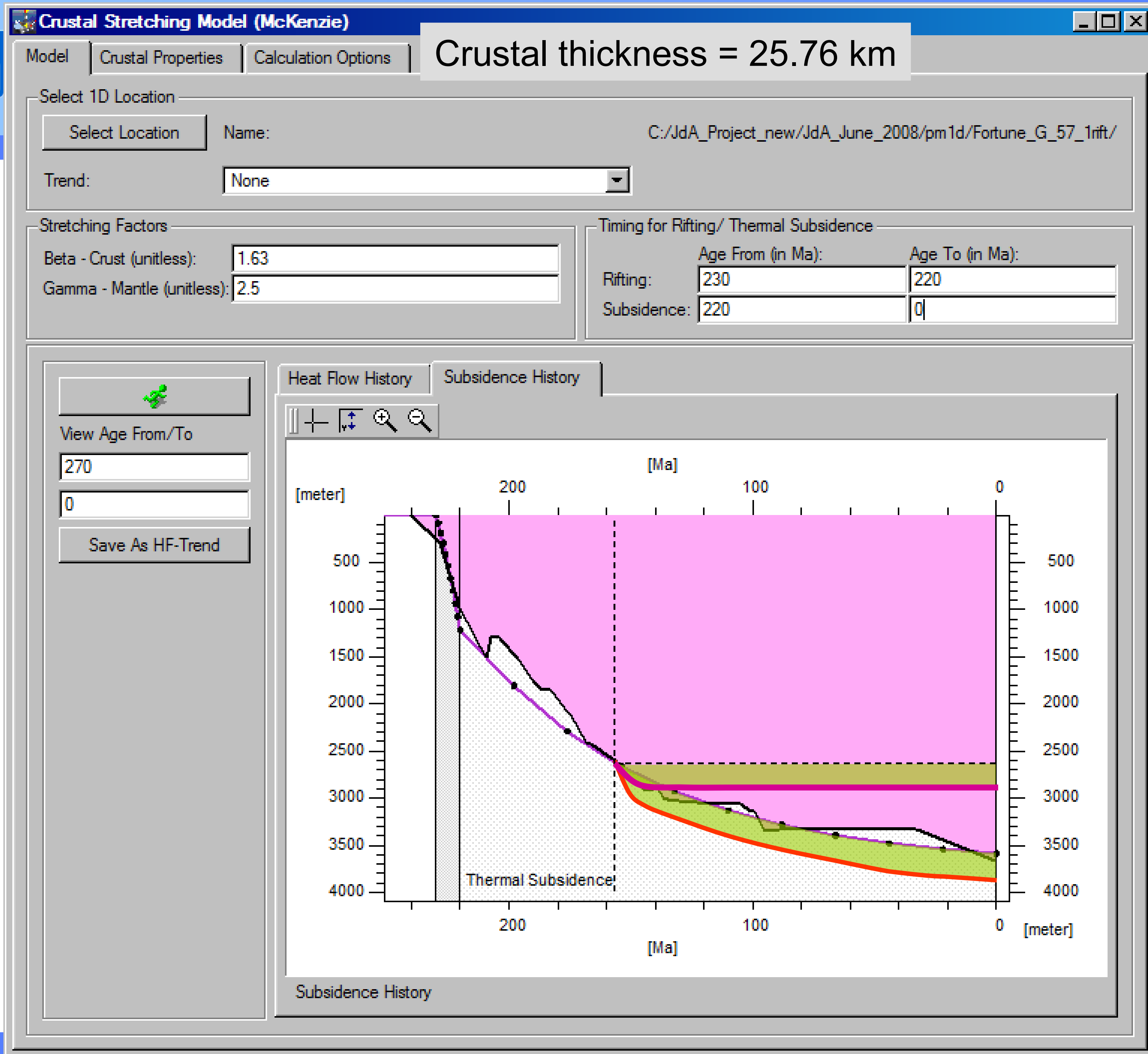


2650 m Tectonic Subs. at 155 Ma

Crustal thickness = 42 km

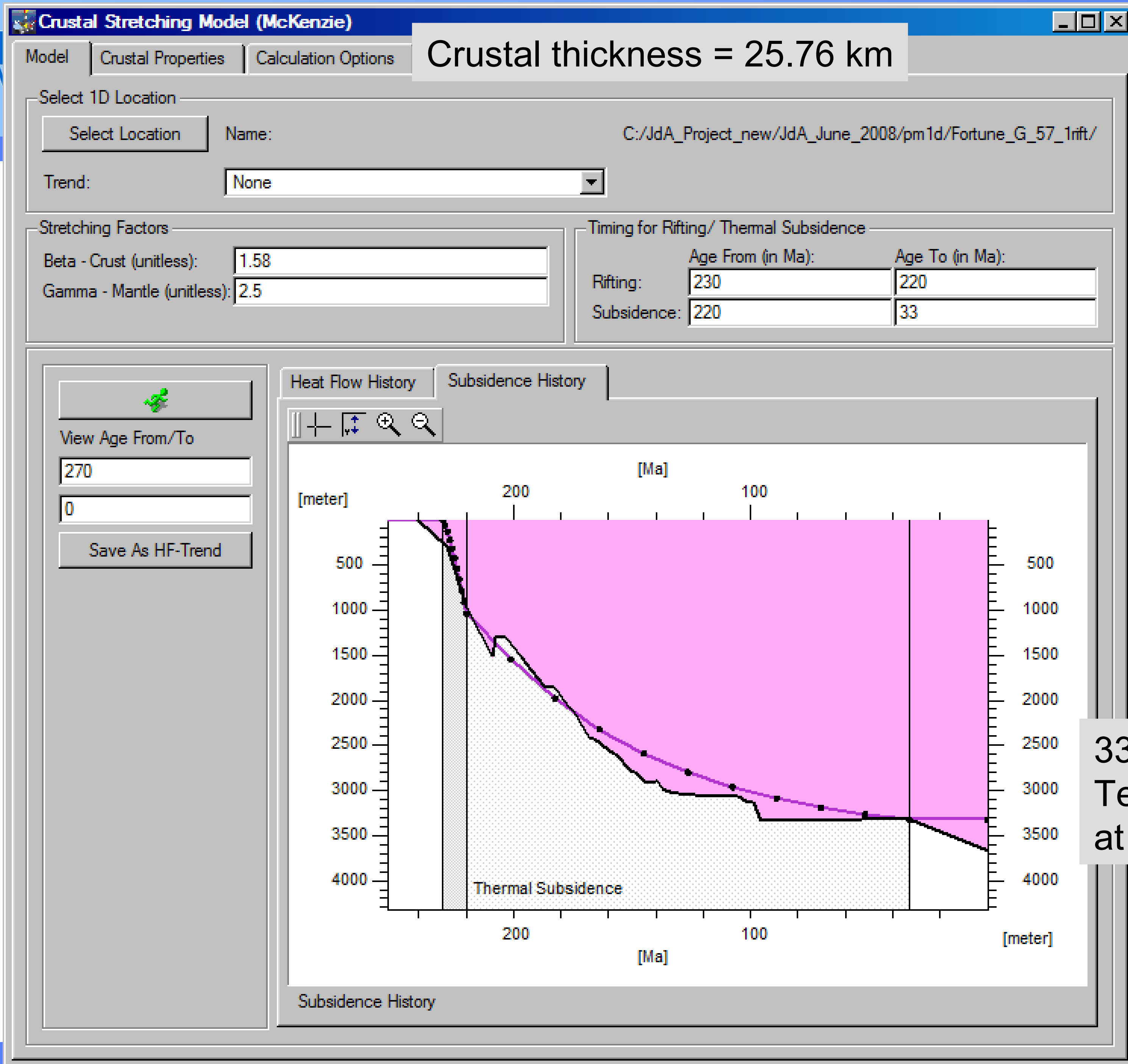



Crustal Stretching Model (McKenzie)
Model
Crustal Properties
Calculation Options
Crustal thickness = 25.76 km
Select 1D Location
Select Location
Name:
C:/JdA_Project_new/JdA_June_2008/pm1d/Fortune_G_57_1rift/
Trend:
None
Stretching Factors
Beta - Crust (unitless):
1.03
Gamma - Mantle (unitless):
1.005
1.03 - 1.03
1.005 - 1.01
Timing for Rifting/ Thermal Subsidence
Age From (in Ma):
Age To (in Ma):
Rifting:
155
145
Subsidence:
145
0
View Age From/To
270
0
Save As HF-Trend
Heat Flow History
Subsidence History
[Ma]
[meter]
200
100
0
500
1000
1500
2000
2500
3000
3500
4000
Thermal Subsidence
Move with Distance
Distance (in m)
2650
Move:
Down
OK
Apply
Cancel
Subsidence History : (x 164.67 Ma, y 0.00 meter)



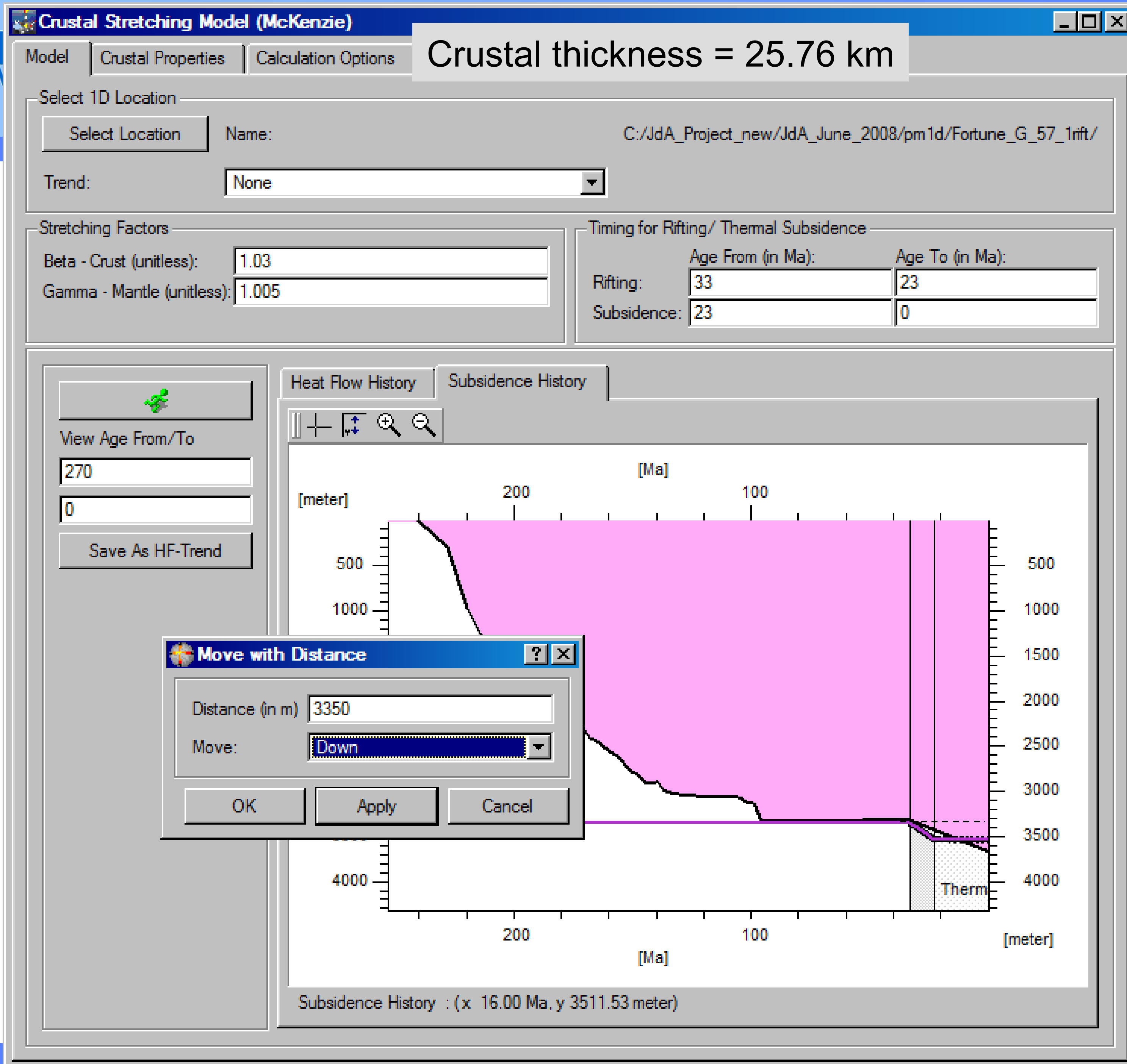
Crustal Stretching Model (McKenzie)
Crustal thickness = 25.76 km
Model
Crustal Properties
Calculation Options
Select 1D Location
Select Location
Name:
C:/JdA_Project_new/JdA_June_2008/pm1d/Fortune_G_57_1rift/
Trend:
None
Stretching Factors
Beta - Crust (unitless): 1.63
Gamma - Mantle (unitless): 2.5
Timing for Rifting/ Thermal Subsidence
Age From (in Ma):
Age To (in Ma):
Rifting: 230 220
Subsidence: 220 0
View Age From/To
270
0
Save As HF-Trend
Heat Flow History
Subsidence History
[Ma]
[meter]
200
100
0
500
1000
1500
2000
2500
3000
3500
4000
Thermal Subsidence
Subsidence History

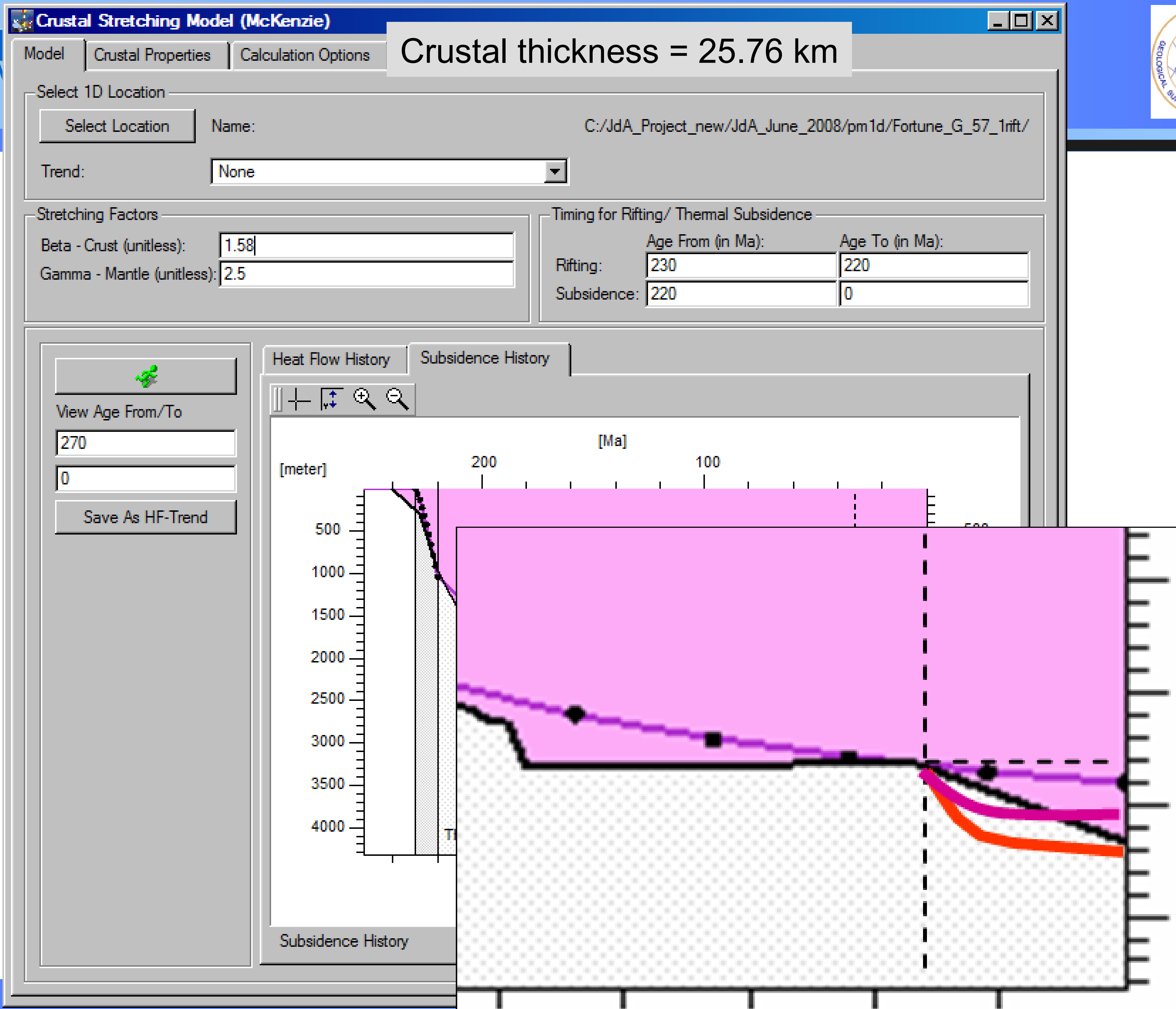
Crustal thickness = 25.76 km



3350 m
Tectonic Subs.
at 33 Ma

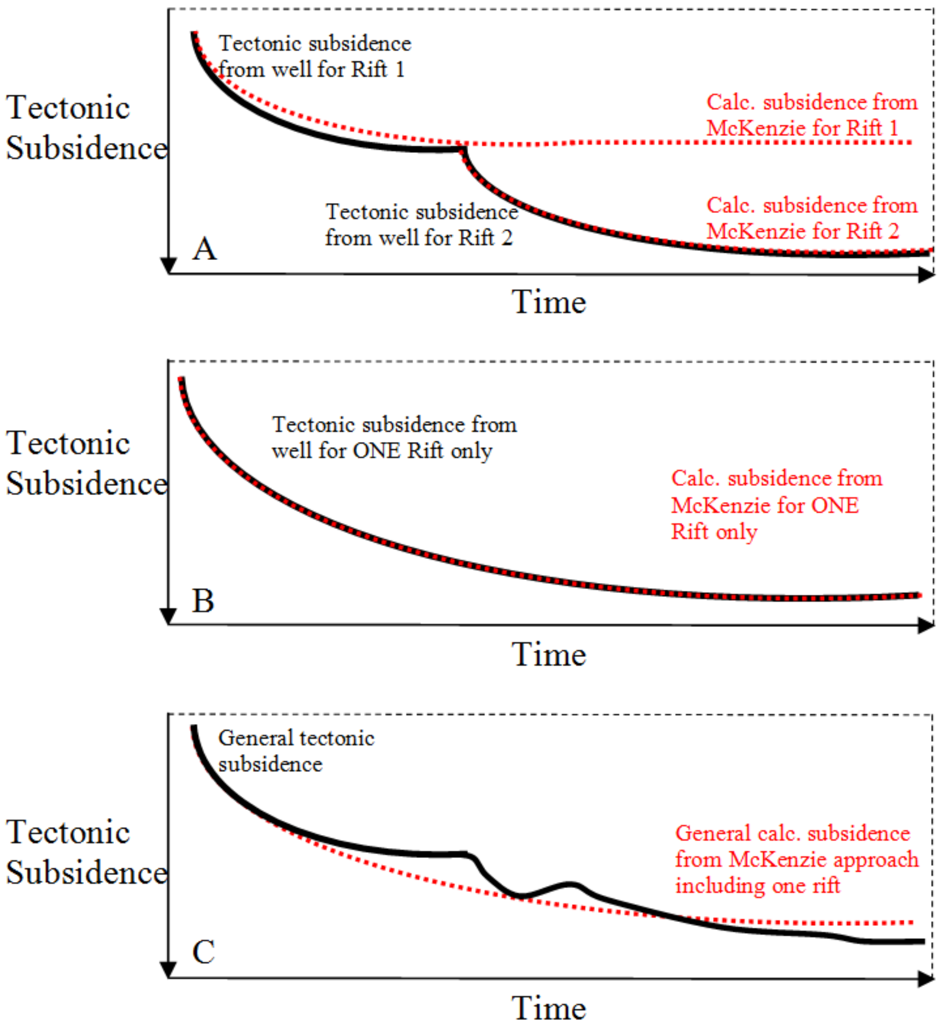
Crustal thickness = 25.76 km





Crustal Stretching Model (McKenzie)
Model
Crustal Properties
Calculation Options
Crustal thickness = 25.76 km
Select 1D Location
Select Location
Name:
C:/JdA_Project_new/JdA_June_2008/pm1d/Fortune_G_57_1rift/
Trend:
None
Stretching Factors
Beta - Crust (unitless):
1.58
Gamma - Mantle (unitless):
2.5
Timing for Rifting/ Thermal Subsidence
Age From (in Ma):
Age To (in Ma):
Rifting:
230
220
Subsidence:
220
0
View Age From/To
270
0
Save As HF-Trend
Heat Flow History
Subsidence History
[Ma]
200
100
[meter]
500
1000
1500
2000
2500
3000
3500
4000
Subsidence History

Summary



2 Rifts Ideally

1 Rift Ideally

Observed

Conclusions

It is easily possible to simulate the tectonic subsidence with just ONE Late Triassic rift event.

The impact of a second thermal event will give for most wells too deep a burial depth for present day situation

Adding a minor Cenozoic thermal event can give a better fit for a few wells.

The thermal effect of a Jurassic rift seems to be small.

The Cenozoic subsidence could be linked to a small thermal event.

The initial Late Triassic rift is the most important one and strong enough to explain the entire subsidence history of the Jeanne d’Arc basin.

Thanks to YOU and to…

Dr. Wielens (GSC)

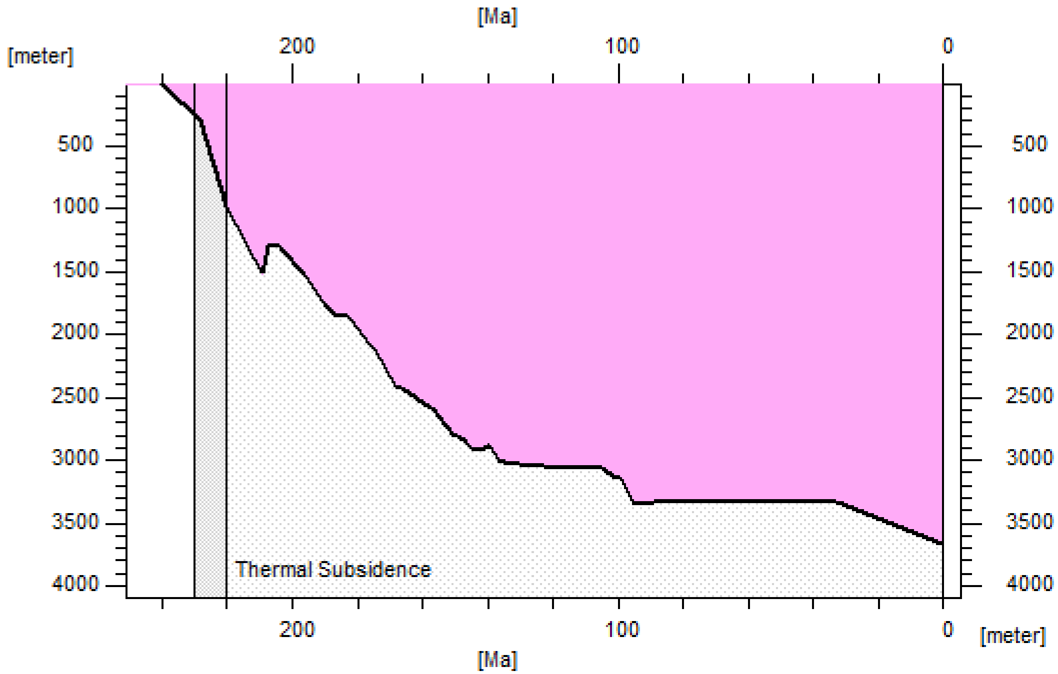
Prof. Littke (RWTH)

Dr. Hawkins (CNLOPB)

IES (Integrated Exploration Systems)

DFG (German Research Foundation)

Tectonic Subsidence



Tectonic subsidence for a water loaded basin

Water = 1 g/cm3
Sediments = 2.6 g/cm3
>> difference between tect. subs. and normal burial should be almost 1/3.

3650 * 2.63 = 9600

>> try to fit the tectonic subsidence !!!

Modelling

Petroleum Systems

1. Mature Source Rock
2. Reservoir
3. Sealing
4. Trap
5. Timing of migration

Modelling

Warning!

Modelling can become addictive!

Guess how I know.....

Questions to ask

- Source potential and type?
- Expected hydrocarbon products?
- Has migration occurred?
- Is source local or distant?
- Time of HC generation and trap formation?
- Amounts of hydrocarbon produced by source?
- Any alteration of reservoir hydrocarbon?

Modelling??

What does it do?

Mathematical simulation of HC generation: 1D - 4D

Requires:

- Lithology (for conductivity + compaction)
- Age Source Rock (for time elapsed) + absolute ages formations
- Heatflow (for temperature)
- Type OM (which kinetic model to use)
- Ro, Tmax, FTA data (to calibrate model)
- Thickness (burial depth)
- Unconformities, Hiatus (missing section) + ages
- Tectonic events (unconformity extent)
- Fluids + flow (heat transport)

Modelling, the TRUTH...

A model is always wrong; parts may be right.

Garbage in, **GARBAGE** out

A model is one big compromise

However:

The model integrates our knowledge

Forces us to think about even “common” knowledge

Parts of the model may be right

The model shows the holes that then can be tackled

What-ifs give us ranges rather than single numbers

More detailed input - better results

Modelling

Result:

- Time of generation
- oil window interval
- trap formation timing correct?
- migration
- HC quantities and quality

- Risk Reduction!!

Modelling in 4D

Basin Analysis Parameters

Sediment distribution

- source facies distribution
- reservoir/ seal facies distribution
- thermal maturation history
- structural evolution and timing of events

Modelling, base

1. Burial and heating

"Geothermal Gradient"

G = dT/dz = Conductivity x heat flow

common number: 24 - 41 °C/km

Translated: bury it deeper and it becomes warmer

Note: different conductivity – different gradient!!

Modelling, base

2. Generate hydrocarbons

Arrhenius equation:

$$k = Ae^{-(E/RT)}$$

- k = reaction rate constant (Ma)
- A = Frequency factor (Ma)
- e = natural exponent
- E = Activation Energy (kJ/mol)
- R = Gas constant
- T = Temperature K

Translated: the kerogen breaks apart into oil and gas in steps

Modelling, base

3. Move it, up

Based on:

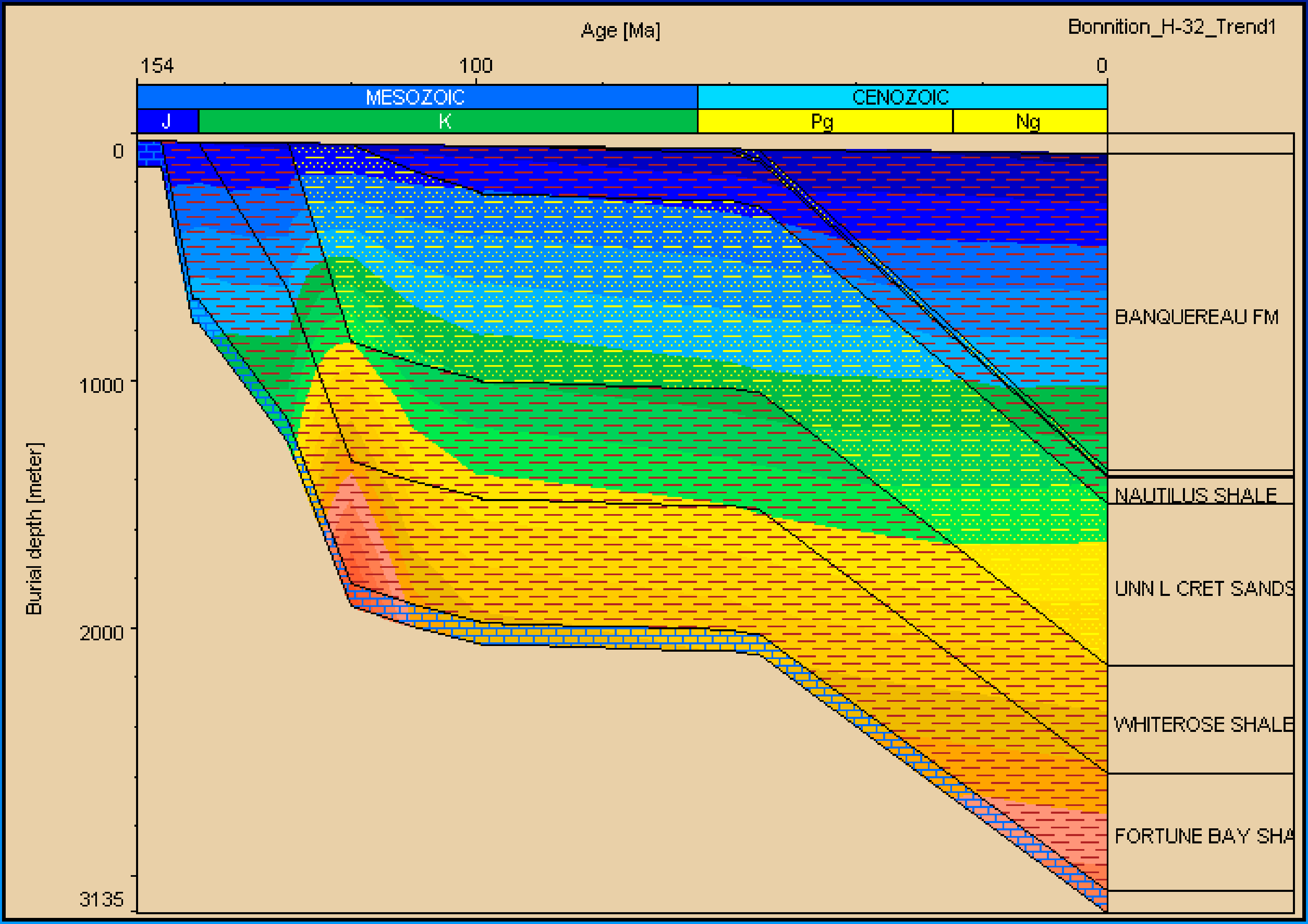
Darcy's Law

$$Q = K/\mu \times \rho A \times d\Phi/dl$$ (Greek to me)

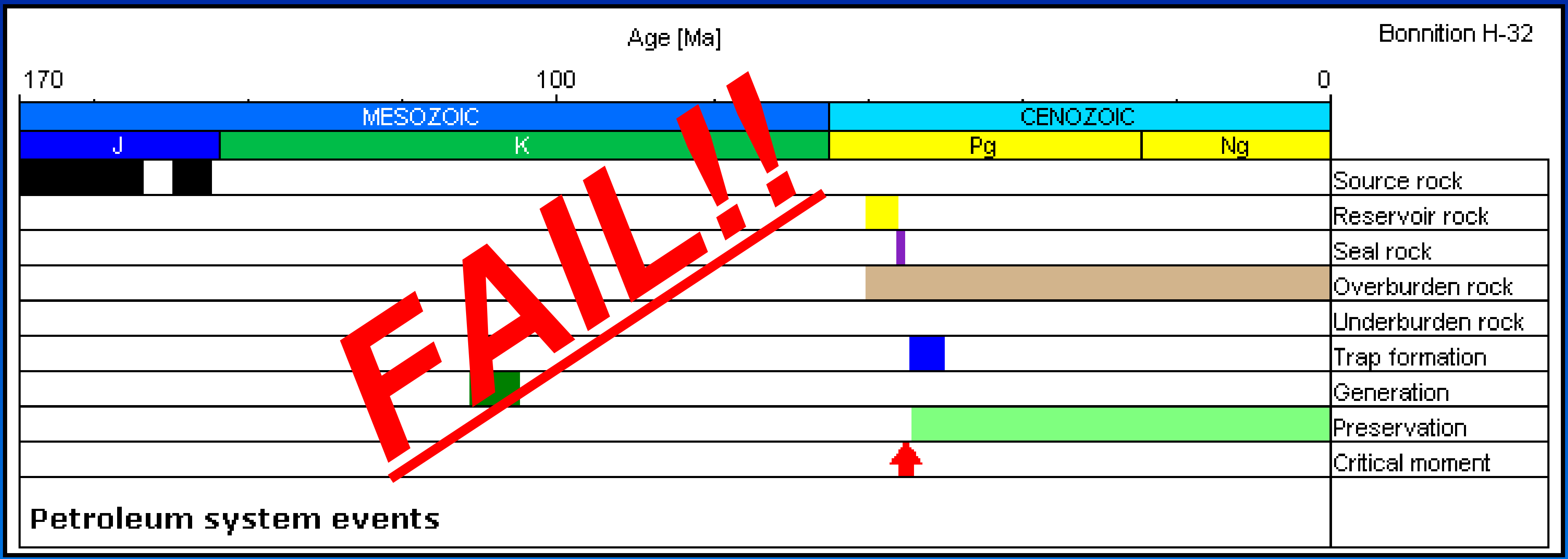
Q = volume flux per time (cm^3/s)
K= intrinsic permeability (darcy)
μ = dynamic viscosity of fluid (cp)
ρ = density of fluid (g/cm^3)
A = cross section of rock with flow (cm^2)
$\delta\Phi/\delta l$ = hydrodynamic gradient along the flow path

Translated: it moves, sometimes with difficulty

Modelling output, a burial history



Modelling output, petroleum system



Modelling, 1D

1D is not for sissies, contrary to common perception!

Needed for calibration, 4D model framework

Friedemann Baur....

Problems: salt

Salt is much more conductive than other sediments

Salt moves on, and reshuffles the basin.

Heatflow & salt from 4D modelling:

Eric Negulic....

Now the painful part...

What goes in???....

- Compose a basin where hydrocarbons can be produced. What would this entail?

- What are the most important elements?

The aspirin...

- Needs sediments, source rock, reservoir, seal, stratigraphic and structural traps, deep enough burial of the source rocks with the existing heat flow to achieve maturity, migration path ways, deformation at the right timing.

- During the formation of the basin, the environments have to be right for OM production and preservation.

- Maturation: Heatflow is least known and has major effect.

Thanks!

You for attending

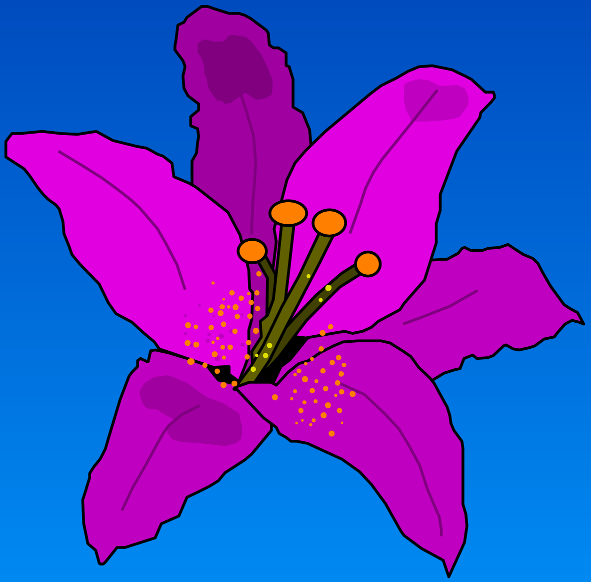
GSC-A for time spent on preparing this

Unger and Lynn Johnston for badly needed humour

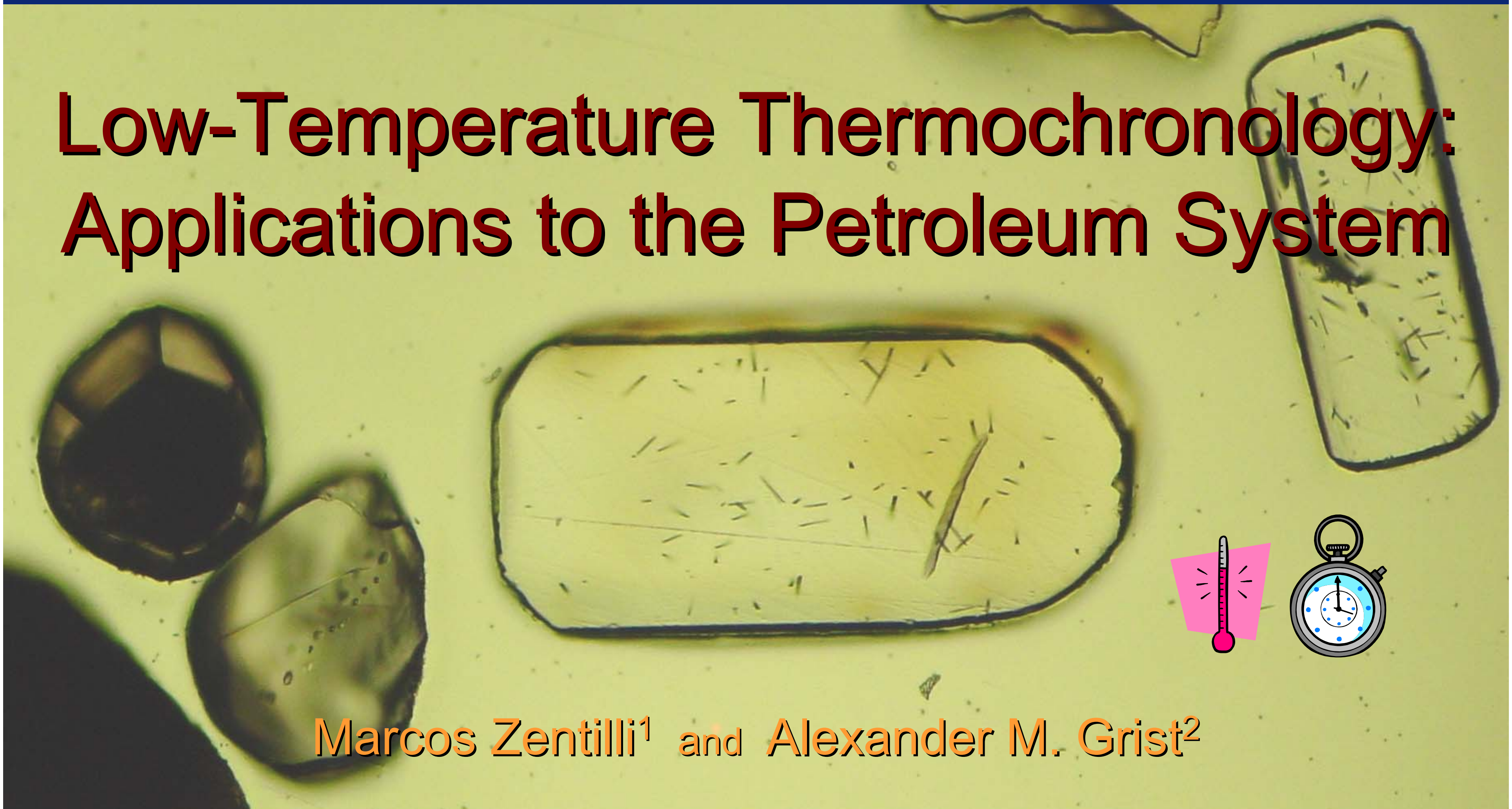
John Hunt, Tissot & Welte for many figures

Let’s play!

IES GmbH



Low-Temperature Thermochronology: Applications to the Petroleum System



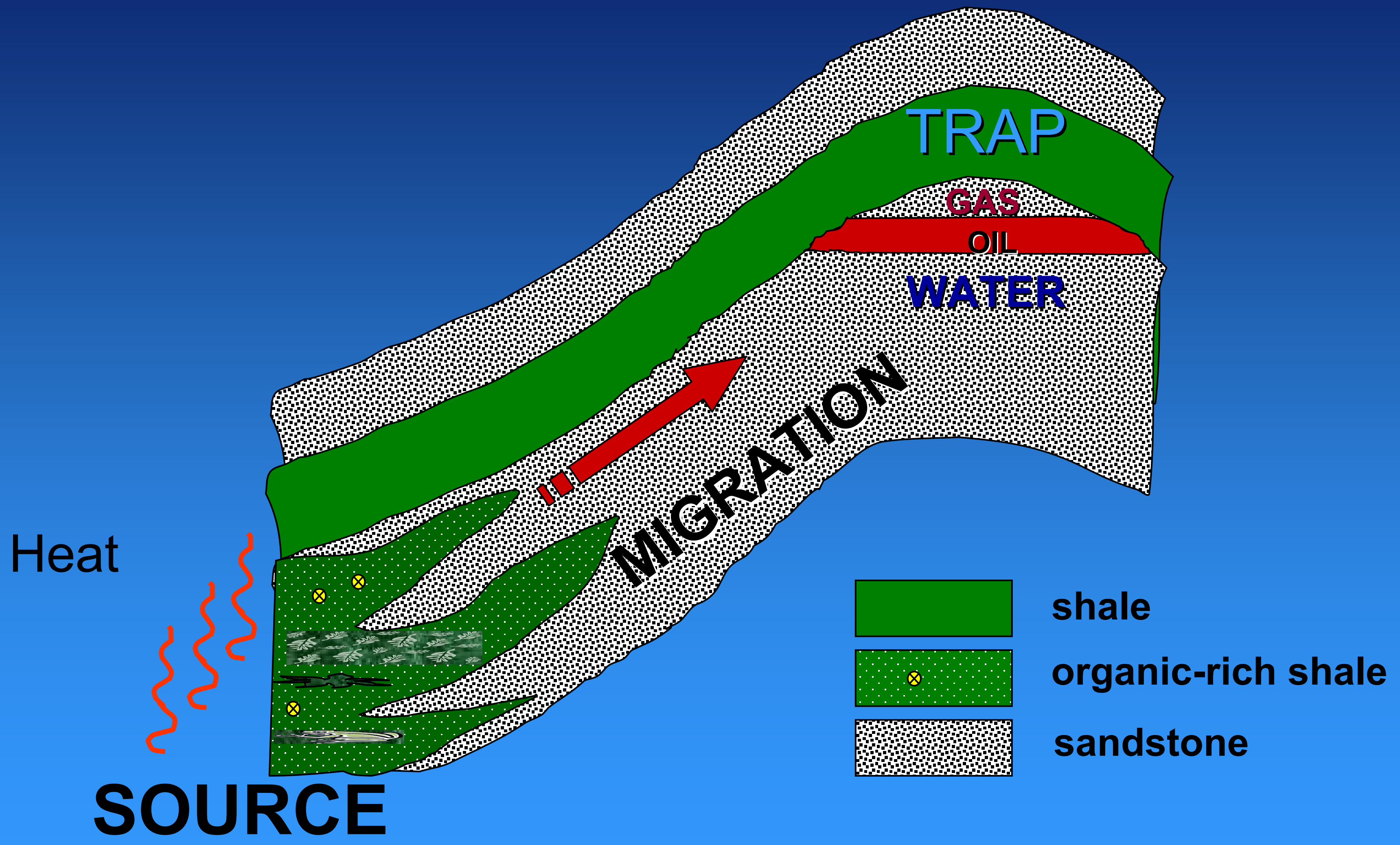
Marcos Zentilli[1] and Alexander M. Grist[2]

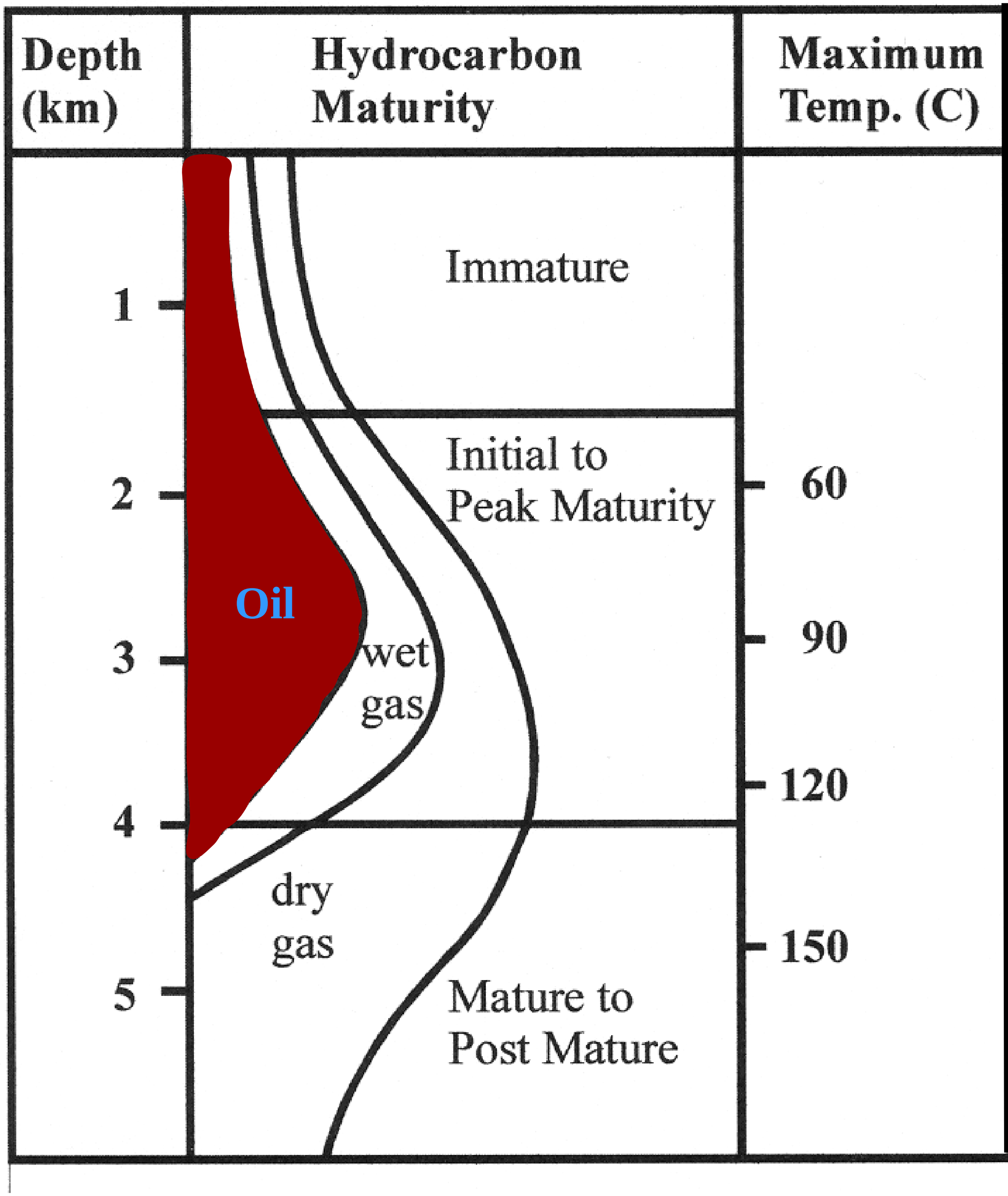
Short Course: Introduction to Petroleum Systems August 11-12, 2008

[1]Dalhousie University, Halifax, Nova Scotia, Canada

[2]University of Queensland, Brisbane, Australia

THE PETROLEUM SYSTEM

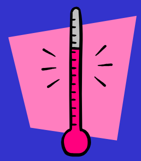
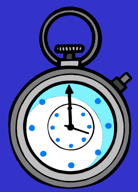




The Oil “Window”

Outline

- **Timing** is fundamental for the Petroleum System
    - Age of strata and surce rocks
    - Age of structures and traps
    - Age and rate of **heating** and **cooling of rocks: THERMO-CHRONOLOGY**
- Thermochronology
    - Apatite Fission Track (AFT)
        - Dating
        - Fission Track Length Time-Temperature Modelling
    - Apatite Uranium-Thorium-Helium (U-Th)/He
- Dating faults
- Basin inversion
- Thermal effect of salt

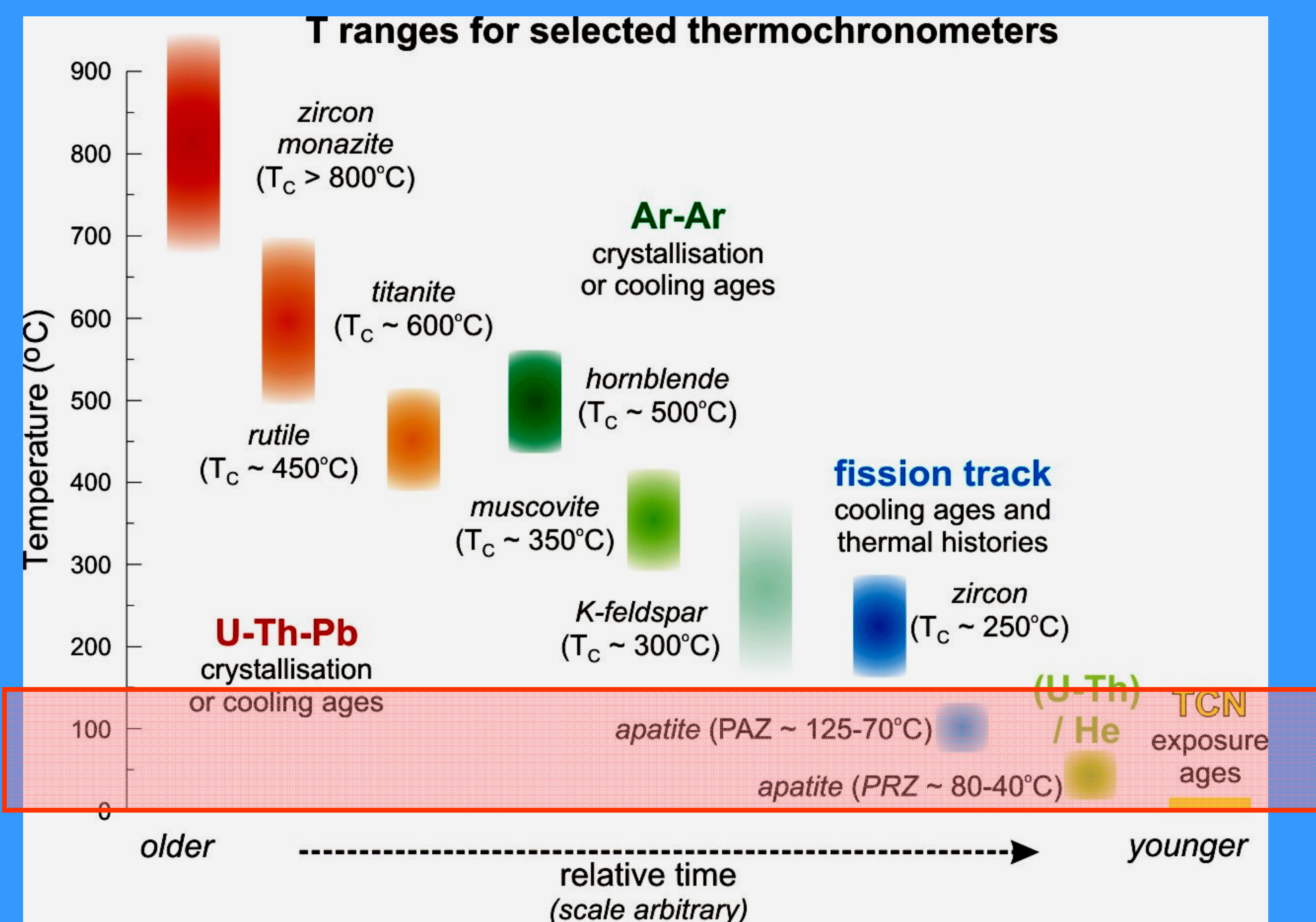
 Thermochronology 

- Dates the time a rock cooled through a certain temperature range: <u>**not its age**</u>

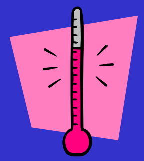
  Clock starts when rock cools down

- < 150^{o}C relevant to Petroleum System

Low-Temperature thermochronology



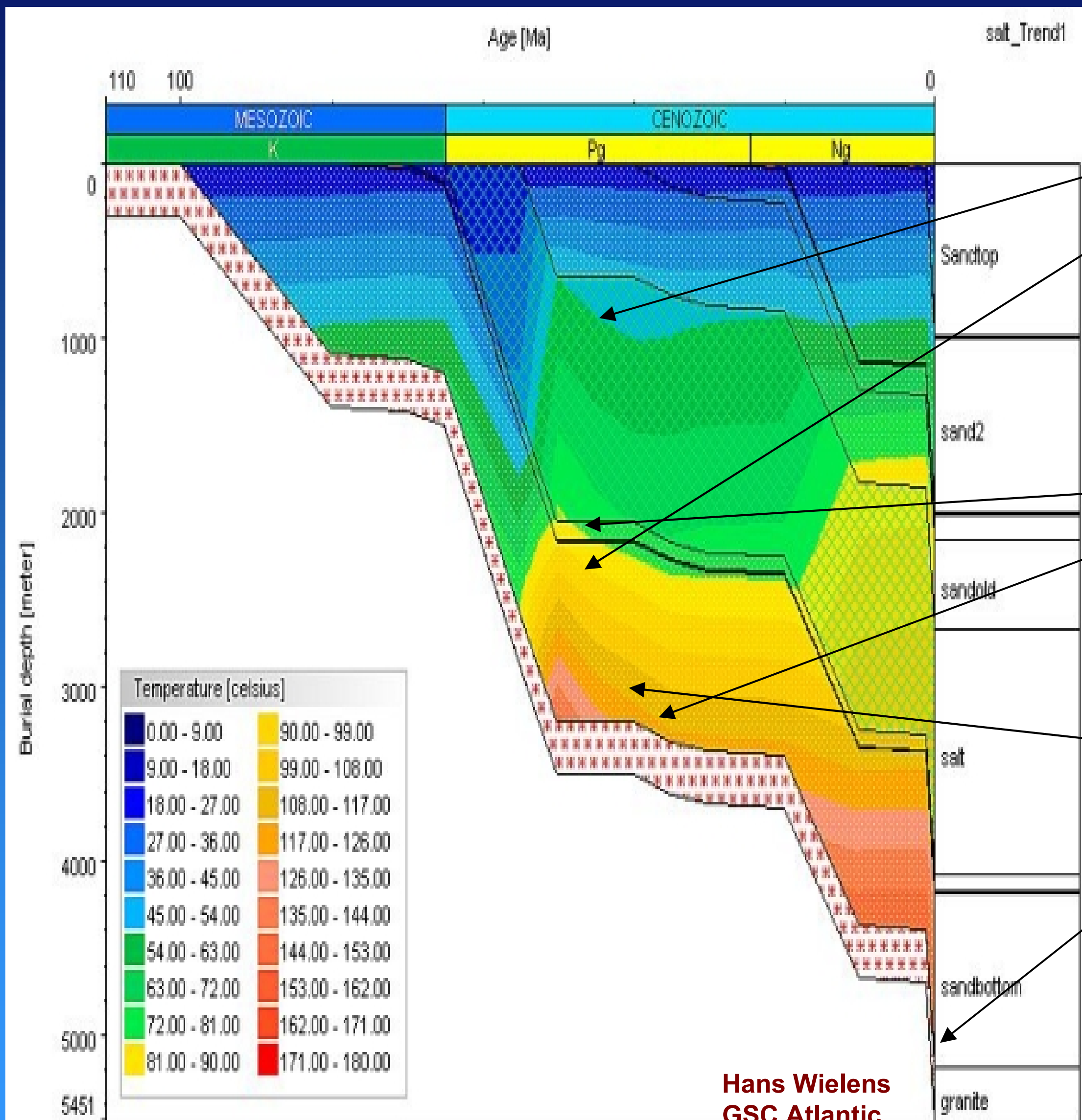
Jamieson 2005



Thermochronology

- **Dates the time a rock cooled through a certain temperature range: <u>not</u> its age**
- < 150^{o}C relevant to Petroleum System

- Apatite Fission Track
  - ~ 100^{o}C
- (Uranium-Thorium)/He
  - Apatite ~ 70^{o}C
  - Fluorite ~ 60^{o}C



(U-Th)/He in apatite temperature range

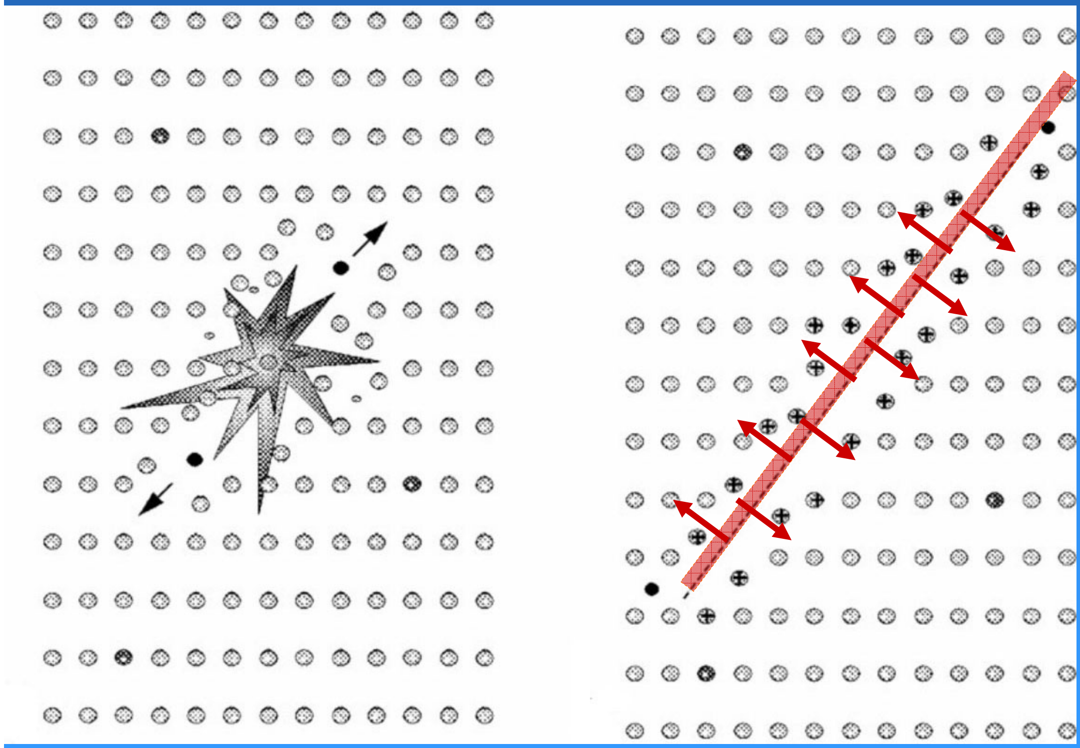
FT in apatite temperature range

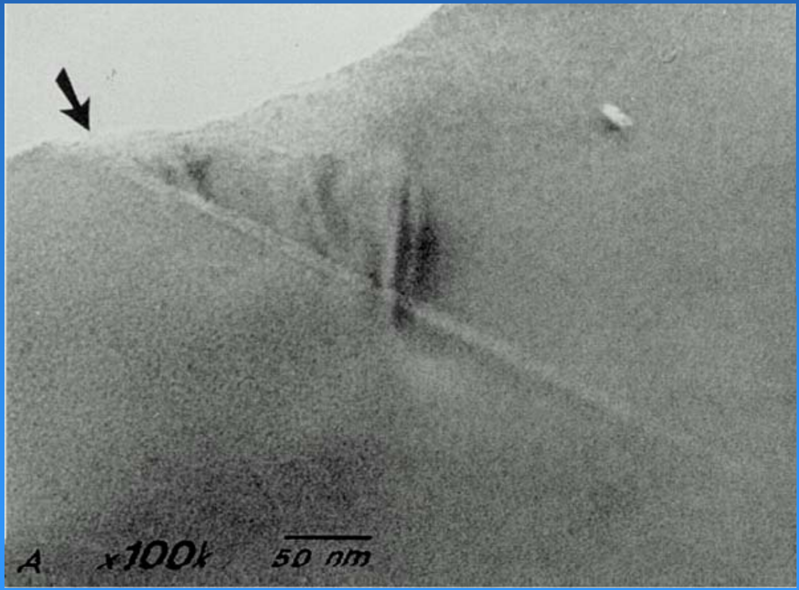
$^{40}Ar/^{39}Ar$ K-Feldspar Zircon FT temperature range

Ion spike model of track formation

(Fleischer et al. 1965)

- Spontaneous fission of 1 atom of ^{238}U (λ_f = ca. 7-8 x10^{-17}/yr)
- Releases 200 MeV of energy and produces highly-charged fission fragments (mass numbers ca. 95 and 135)
- electrons stripped from lattice
- secondary positive ions displaced into lattice by mutual repulsion

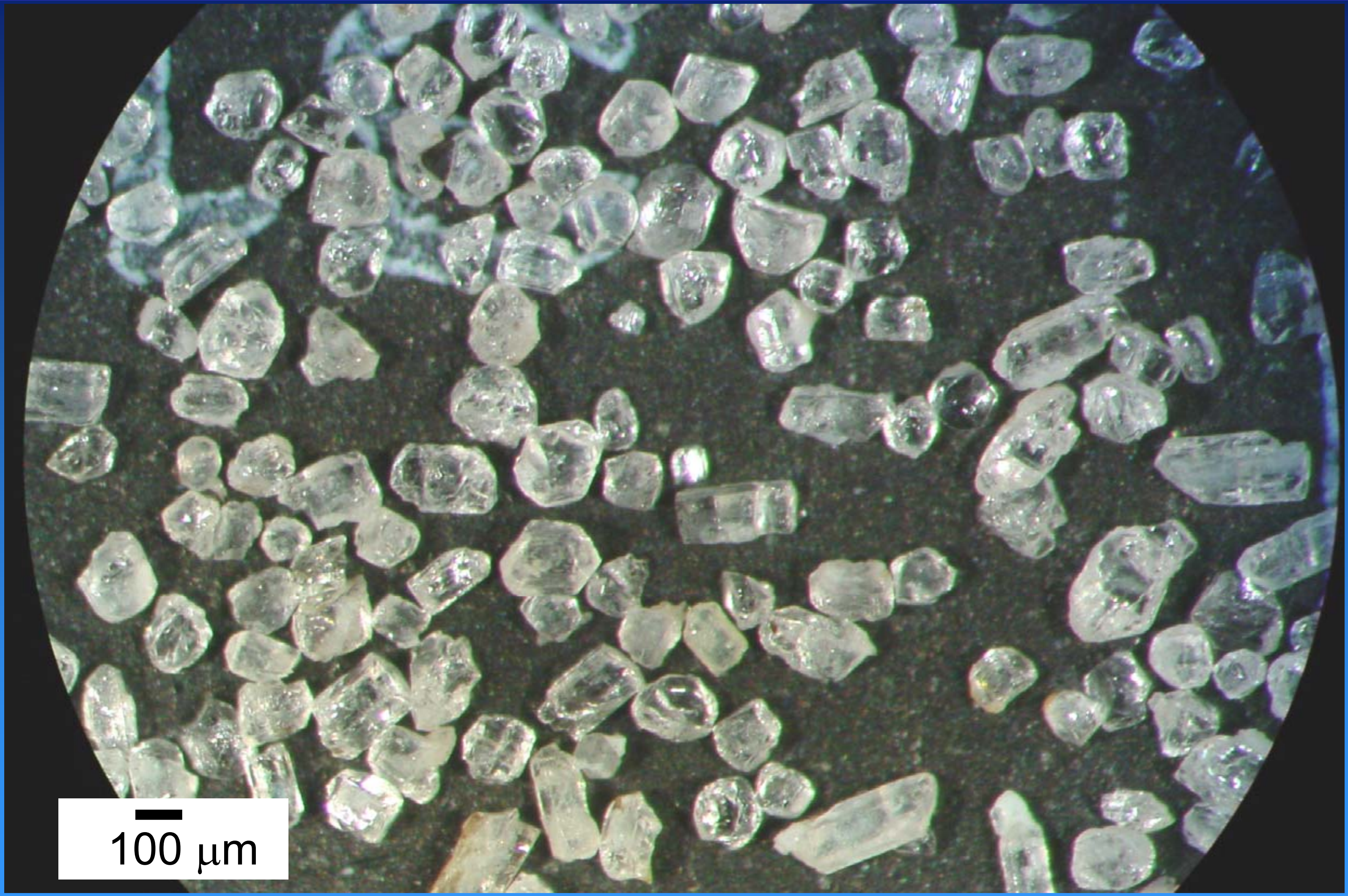




TEM image of latent fission track

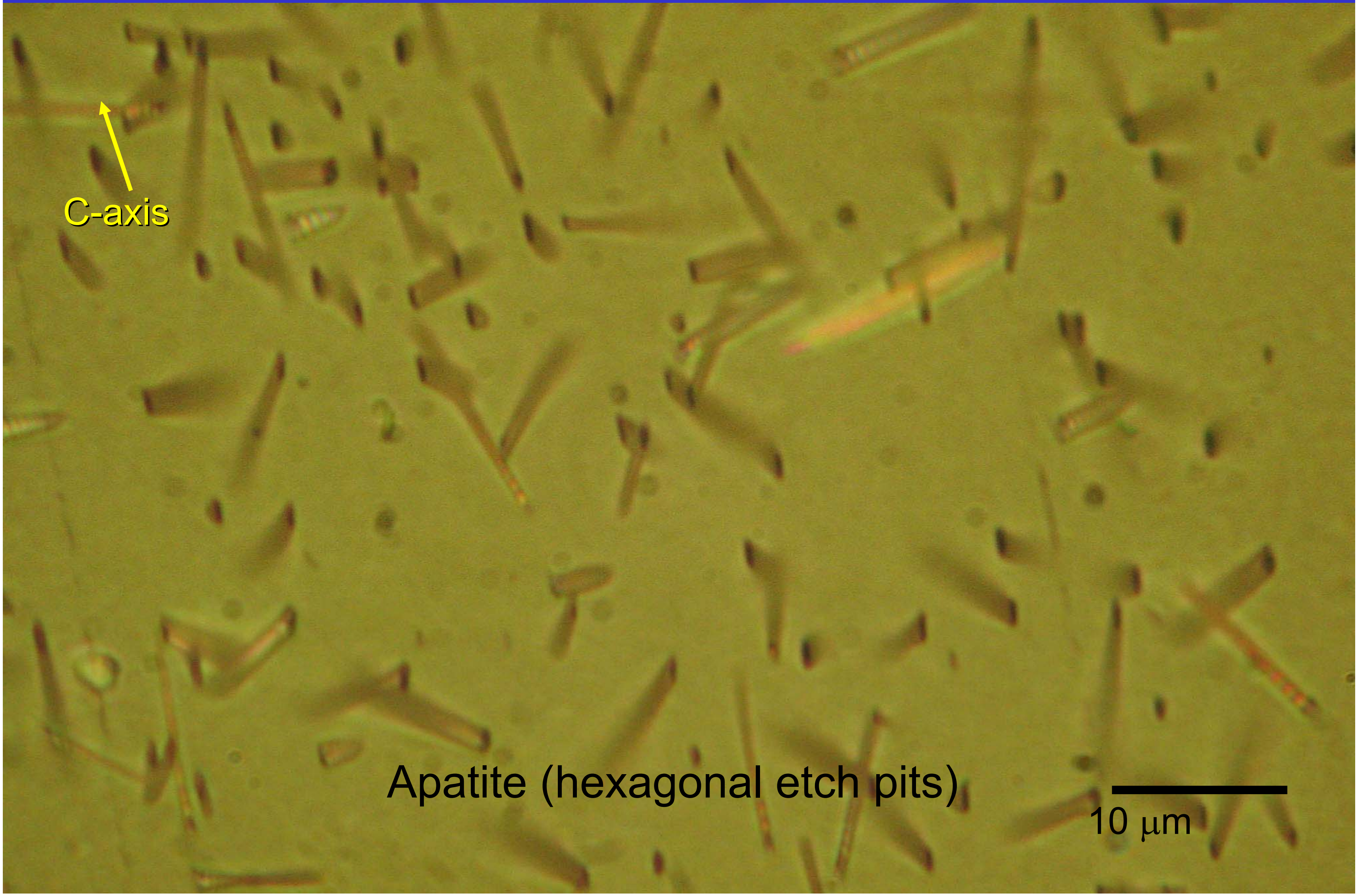
(Paul and Fitzgerald, 1992)

Sample preparation (Apatite: $Ca_5(PO_4)_3(F,Cl,OH)$)



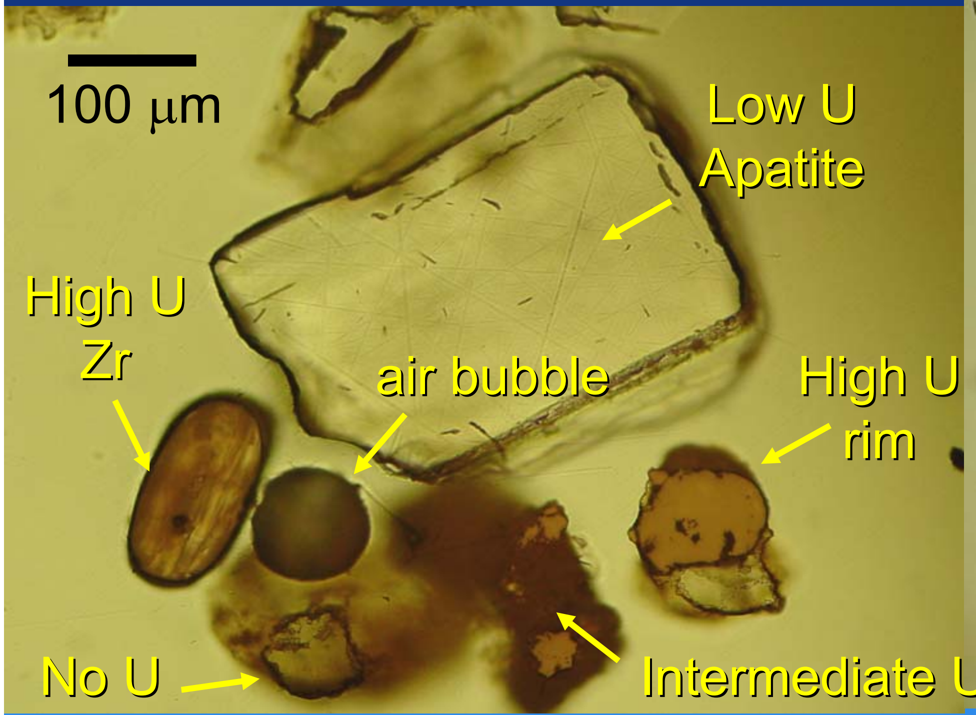
Crushing to sand size → heavy liquids → magnetic separation

Mounted, Polished and Etched Fission Tracks



FT dating: Parent, Daughter, λ constant

$^{238}U\ \lambda_f$ = ca. 7-8 x10 $^{-17}$/yr ($t_{1/2}$ = ~9.9 x 10^{15} yr)



Latent fossil tracks accumulate through time in U-bearing mineral phases.

Irradiation with thermal neutrons induces ^{235}U fission, and gives a measure of the U distribution.

FT dating: basic age equation

$$t = \frac{1}{\lambda_d} \ln \left[1 + \frac{\lambda_d \phi \sigma I \rho_s}{\lambda_f \rho_i}\right]$$

Where:

t = age

λ_d = ^{238}U total decay constant; 1.551 x10^{-10}/yr (e.g. Hurford 1990)

λ_f = ^{238}U fission decay constant; ca. 6.9-8.4 x10^{-17}/yr (e.g. Fleischer and Price, 1964; Spadavecchia and Hahn, 1967; Roberts et al. 1968; Friedlander et al. 1981)

ϕ = the thermal neutron fluence

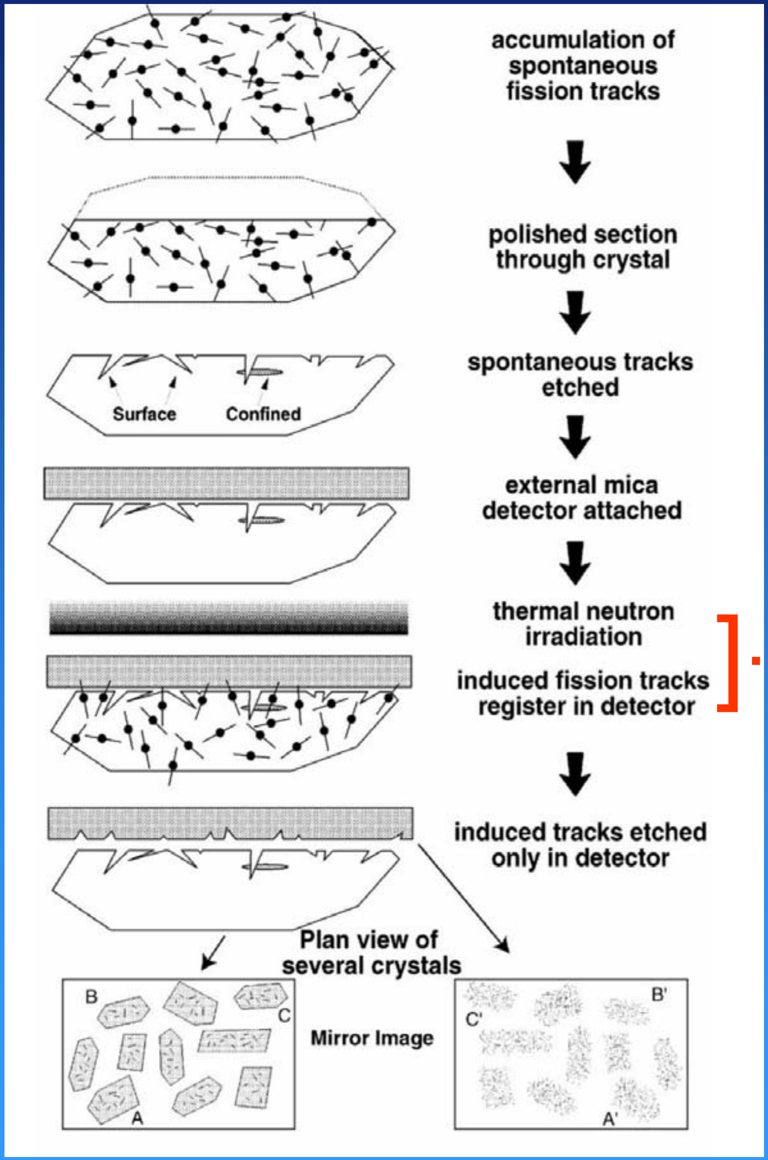
σ = the thermal neutron cross section; ca. 580 x10^{-24} cm^2 (e.g. Hurford 1990)

I = $^{235}U/^{238}U$ isotopic abundance ratio; 7.2527 x10^{-3}

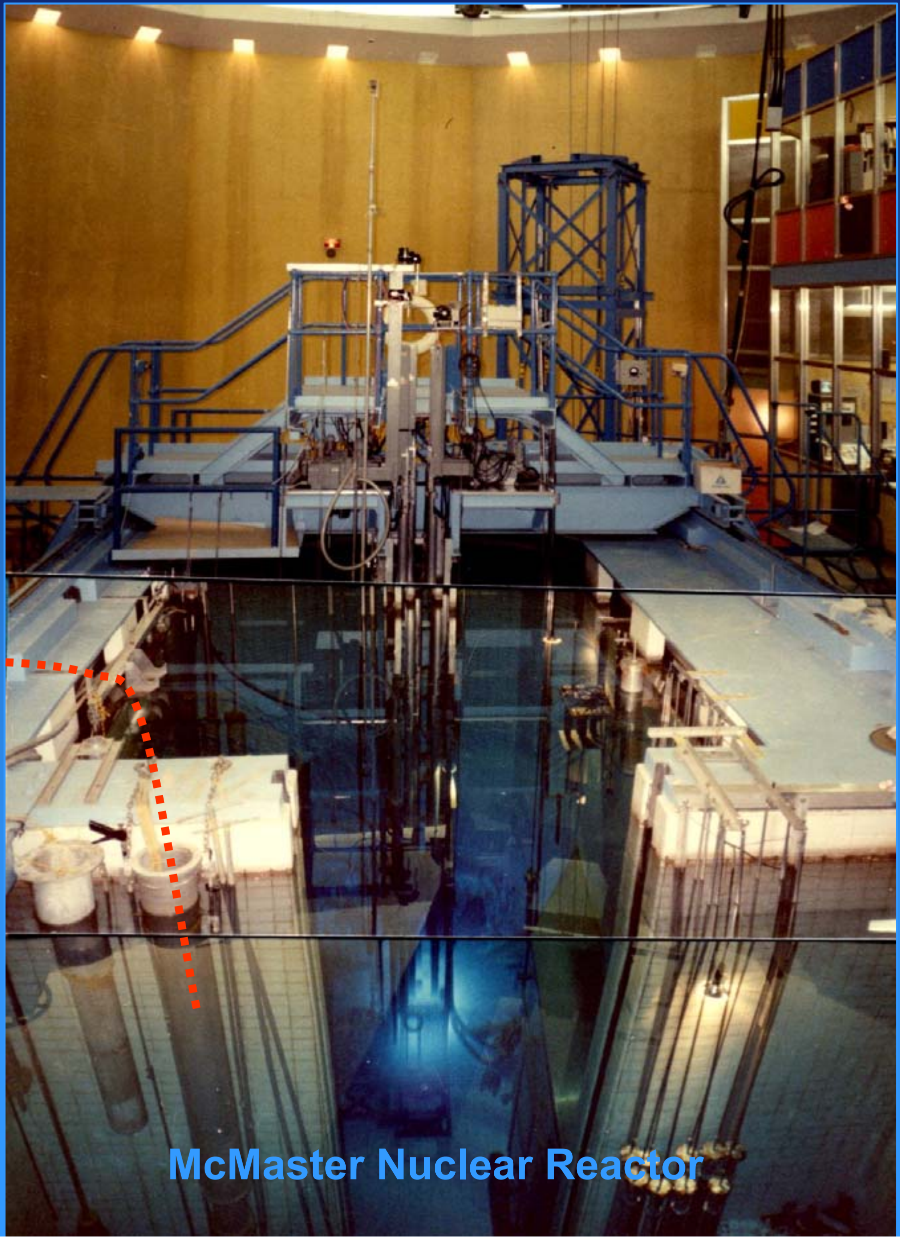
ρ_s = spontaneous track density

ρ_i = induced track density

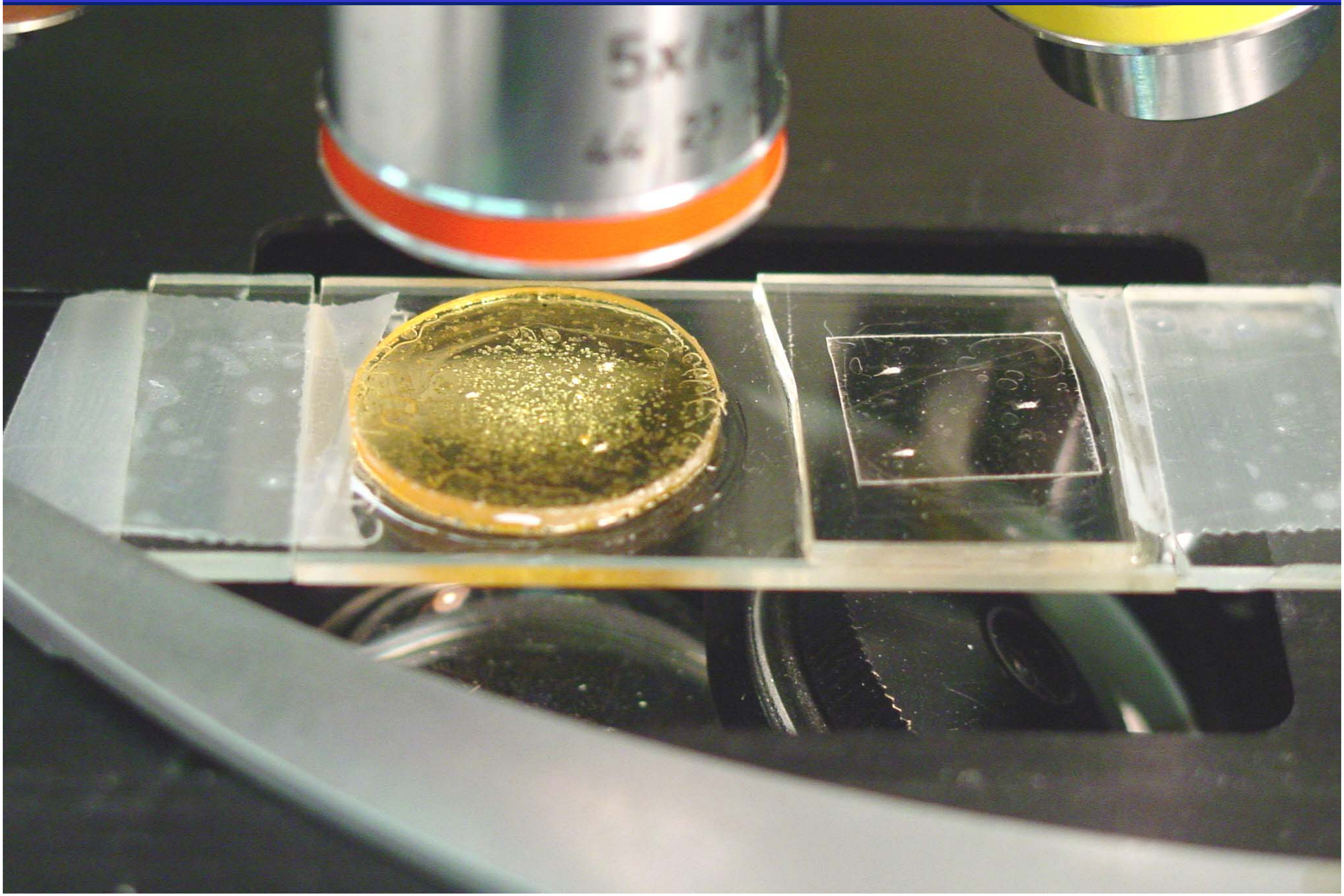
FT age by external detector method



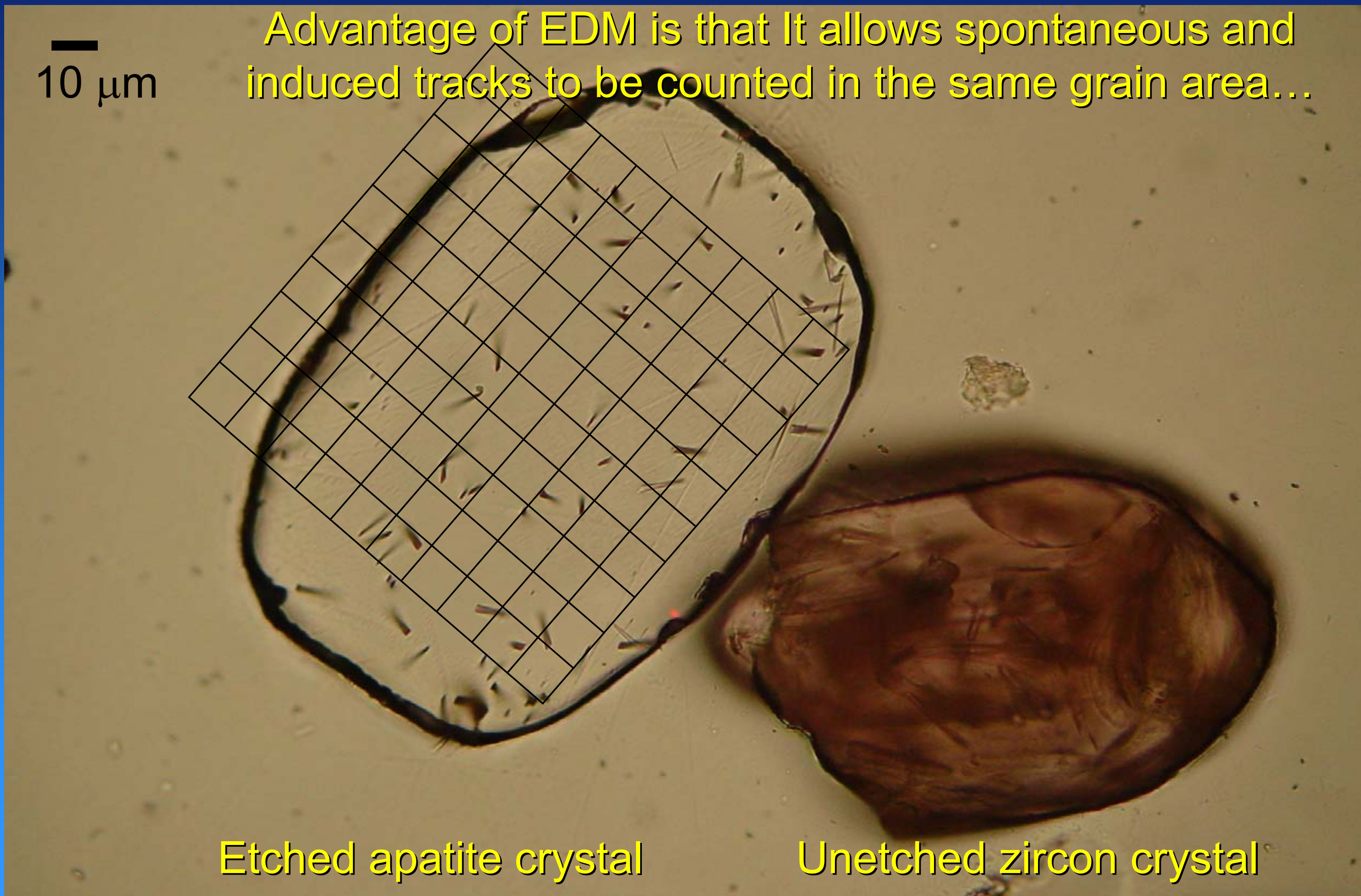
(Hurford and Carter, 1991)



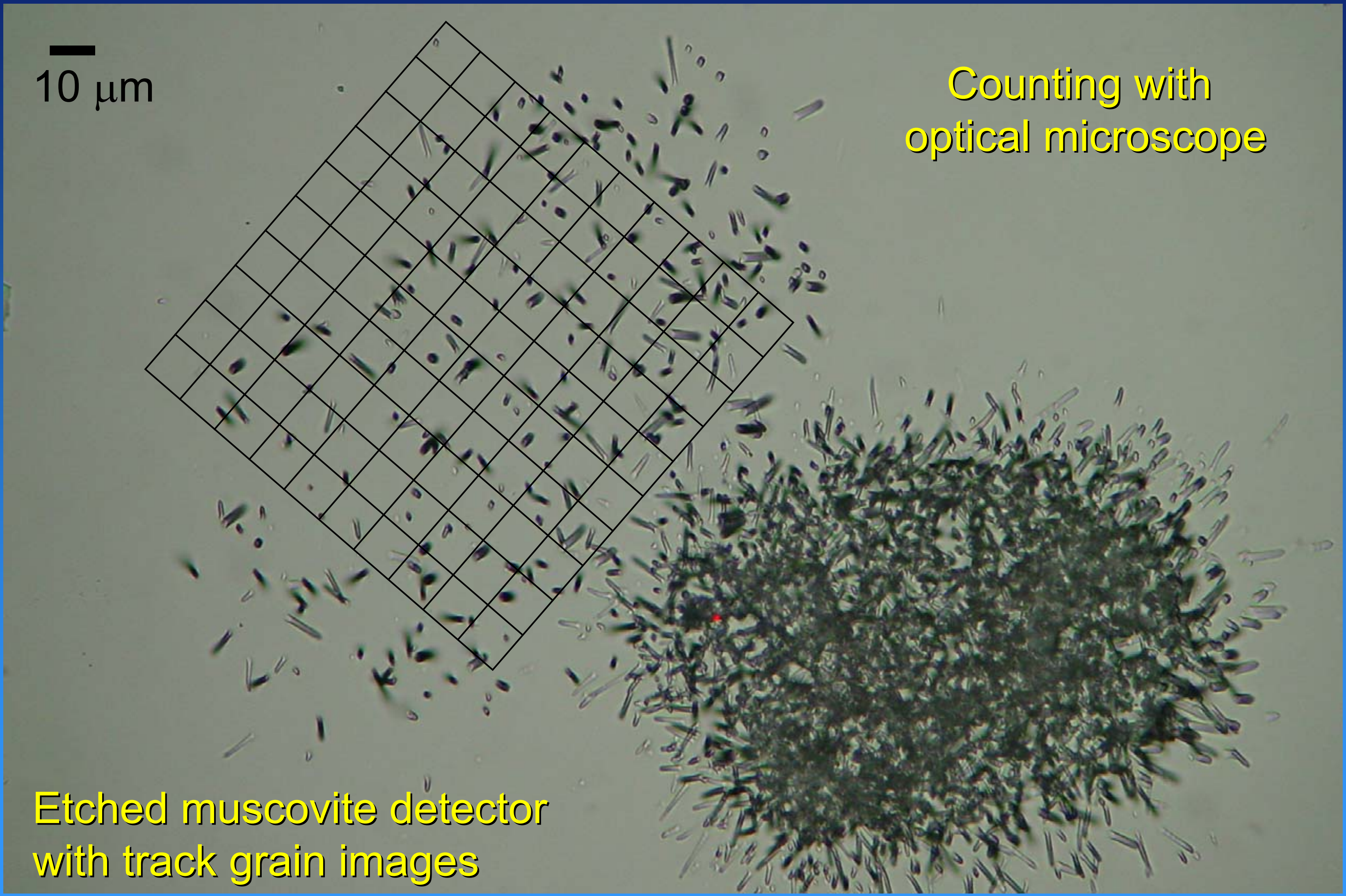
Fission track counting



FT dating: external detector method

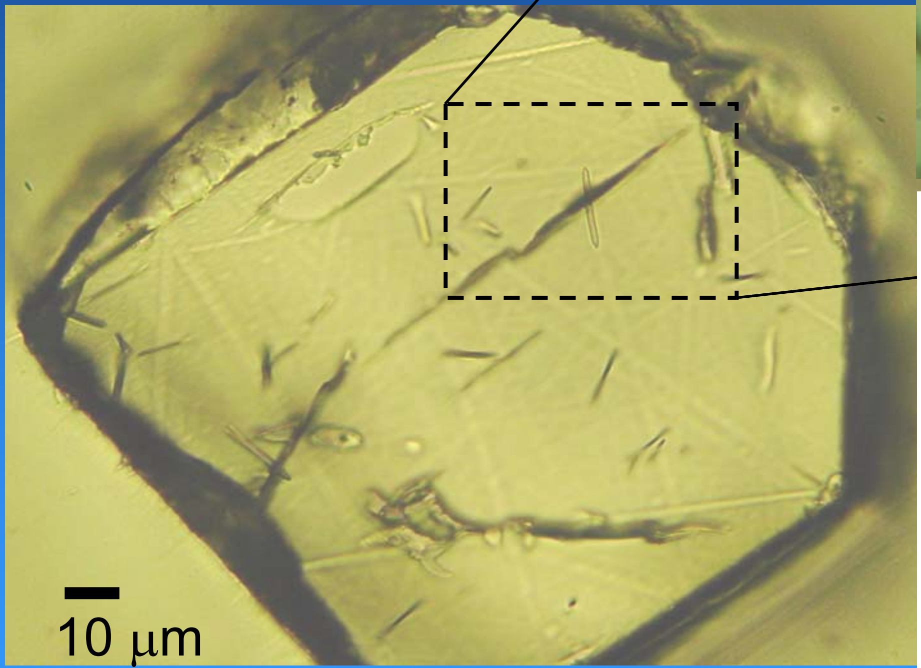


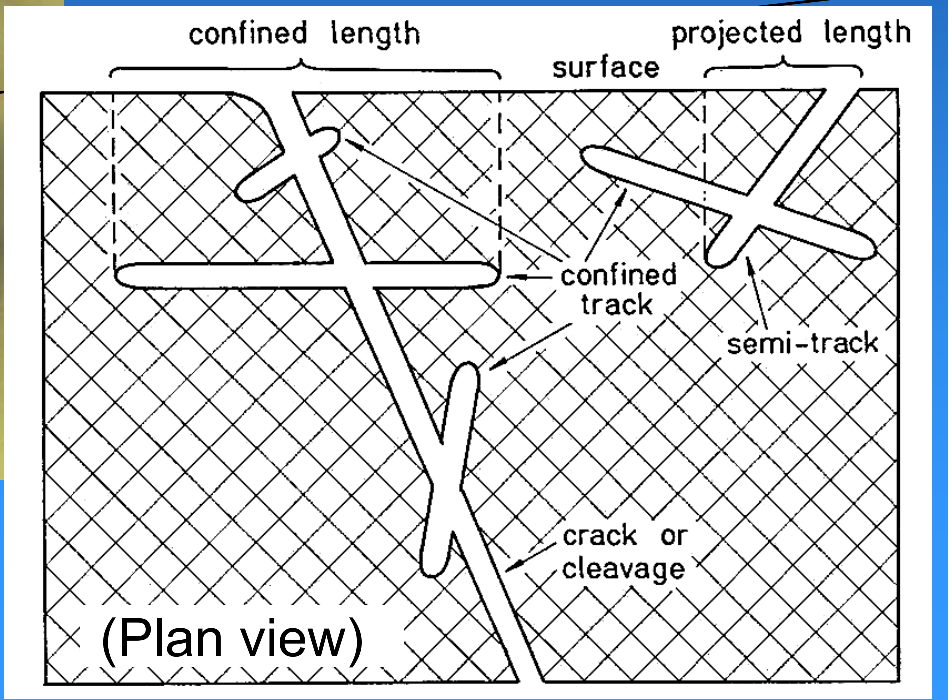
FT dating: external detector method



Confined track lengths:

Tracks which don't intersect the polished surface, but do intersect surface tracks (TINT) or a crack/cleavage (TINCLE)

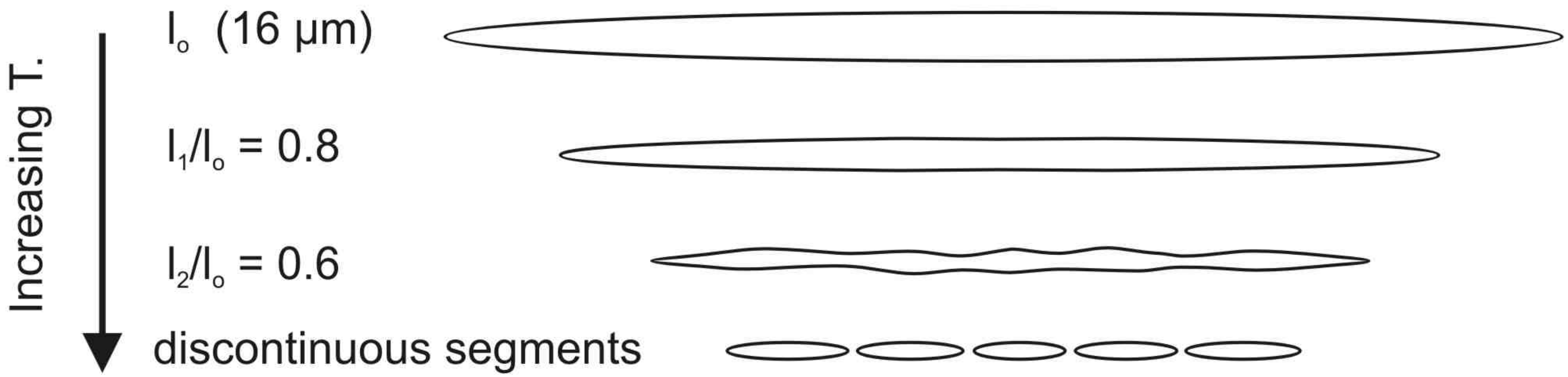




(Wagner and van den Haute, 1992, after Gleadow et al. 1983)

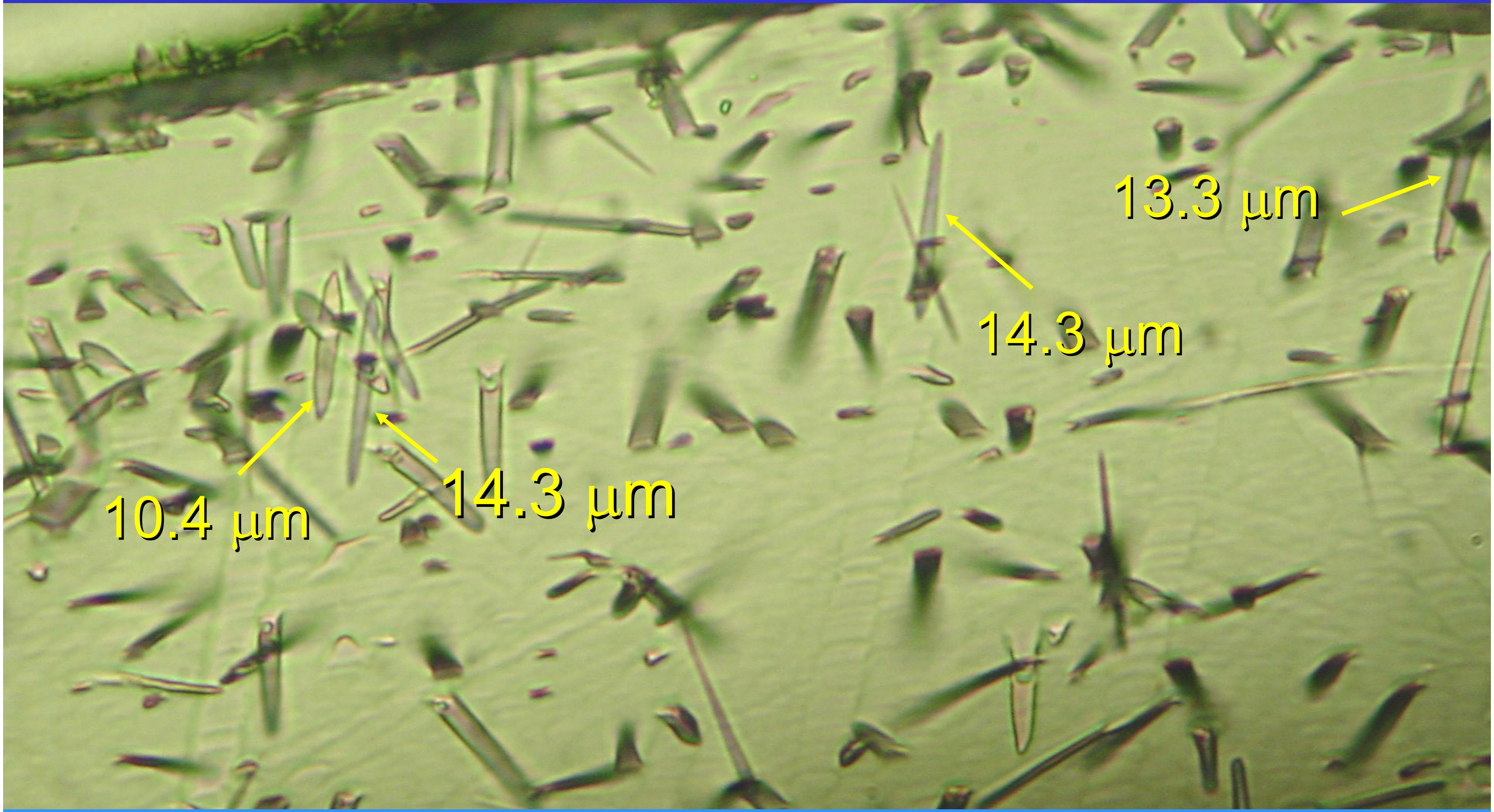
Track length shortening due to heating:

Heating of unetched tracks causes **diffusion** of displaced ions within the crystal lattice resulting in progressive reduction of the etchable length of the latent track to 60-65% of the initial length.



(schematic; tremendous vertical exaggeration)

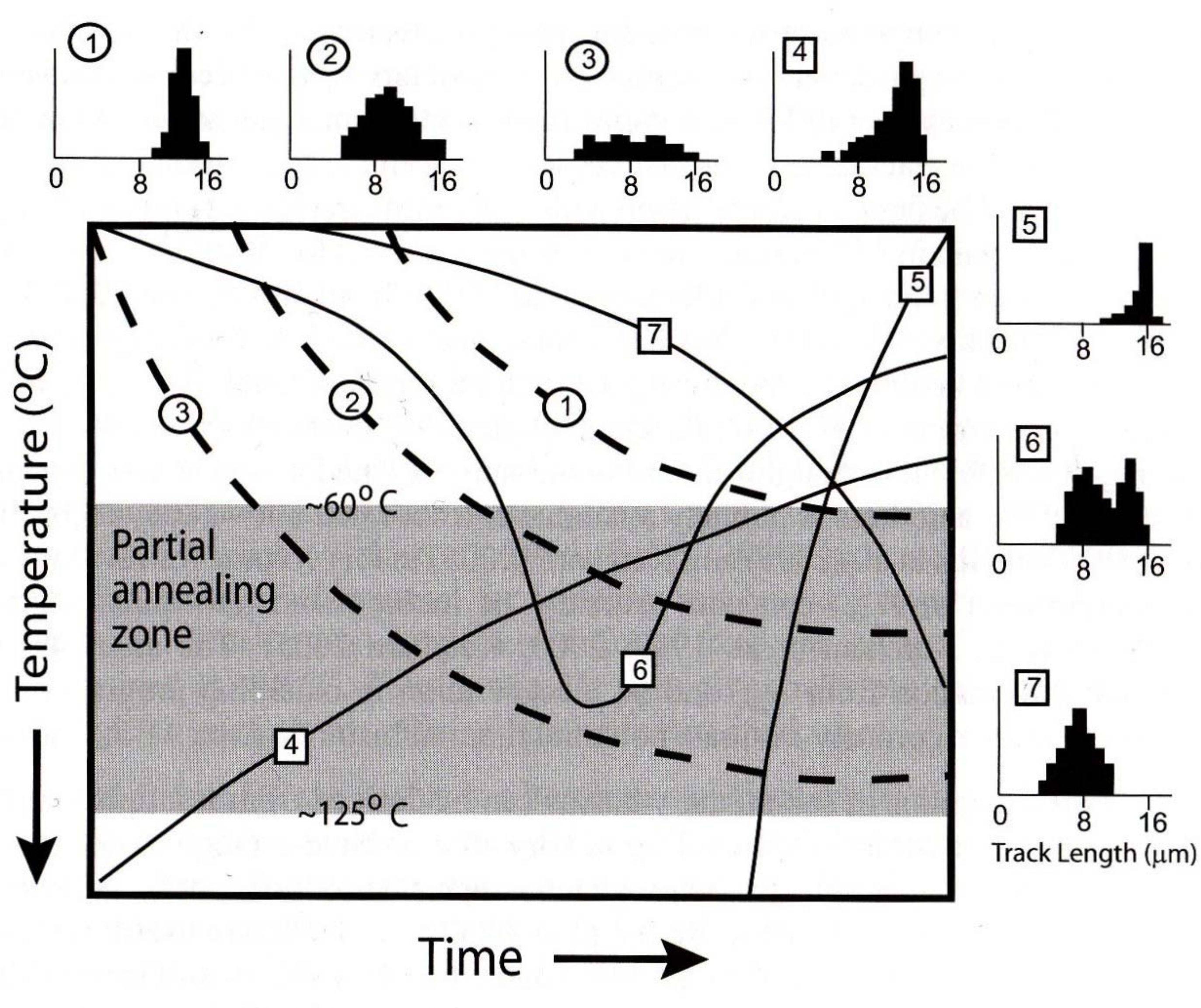
(Apatite) TL thermochronology



Tracks are formed continuously through time.
Within a grain **short** tracks are **older** than **long** tracks

TL thermochronology

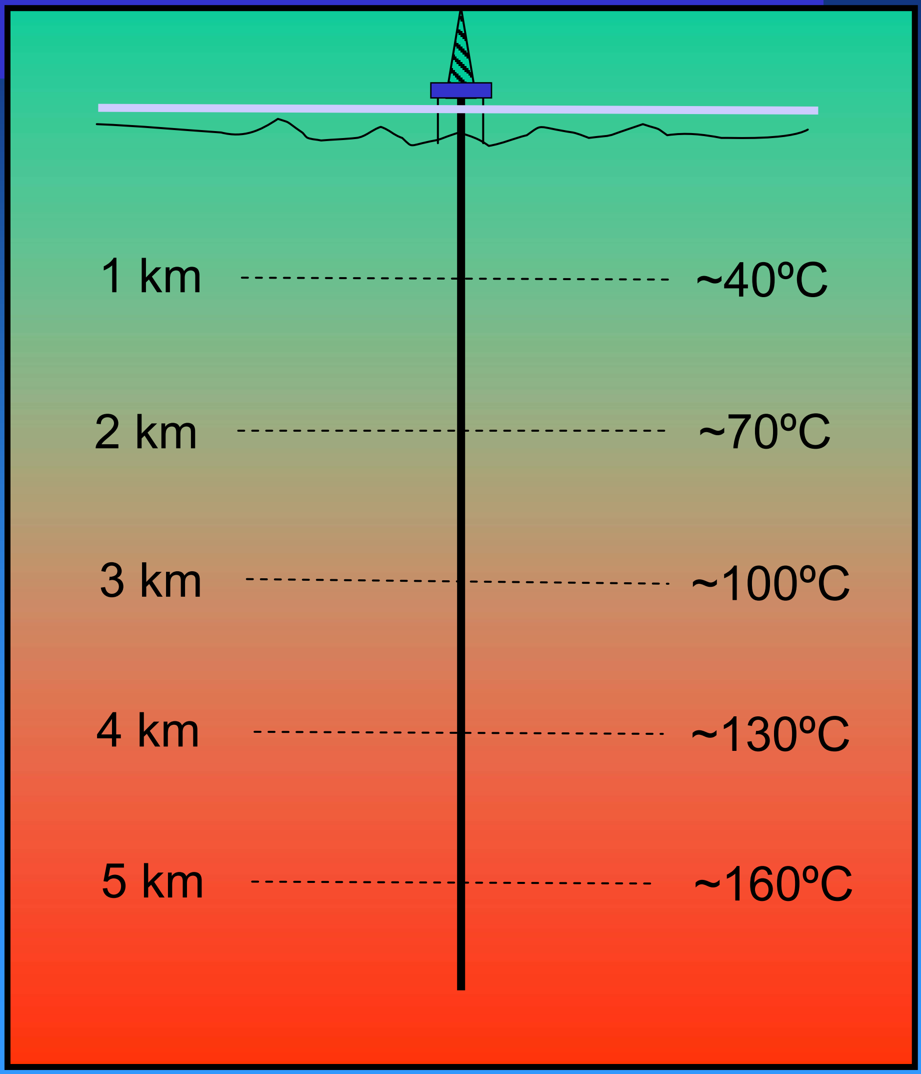
Track-Length distributions are indicative of thermal history

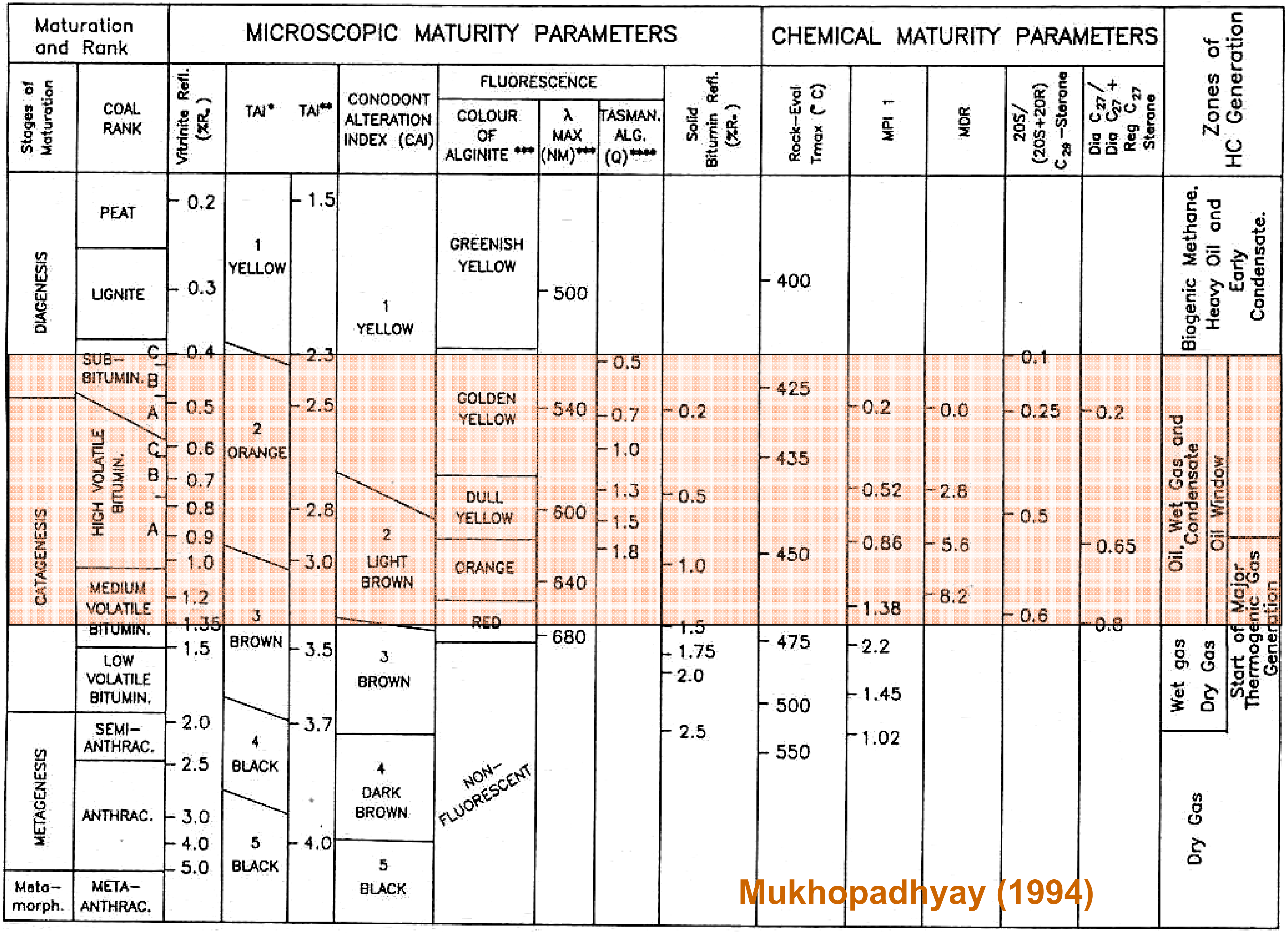


(Gleadow et al. 1983)

Geothermal Gradient

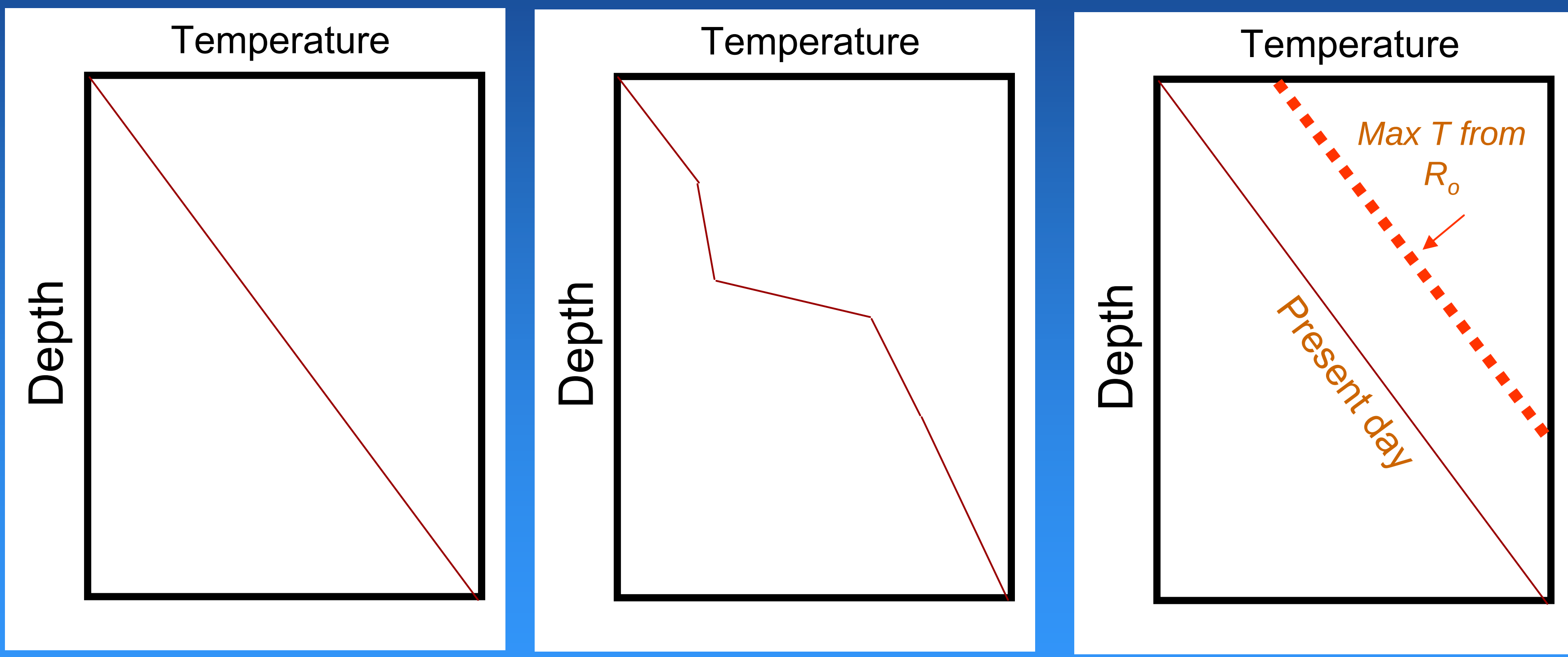
- **Temperature increases with depth (~30ºC/km)**
- **G.G. Varies with**
  - **Tectonic regime**
  - **Thermal conductivity**
  - **Overpressures**



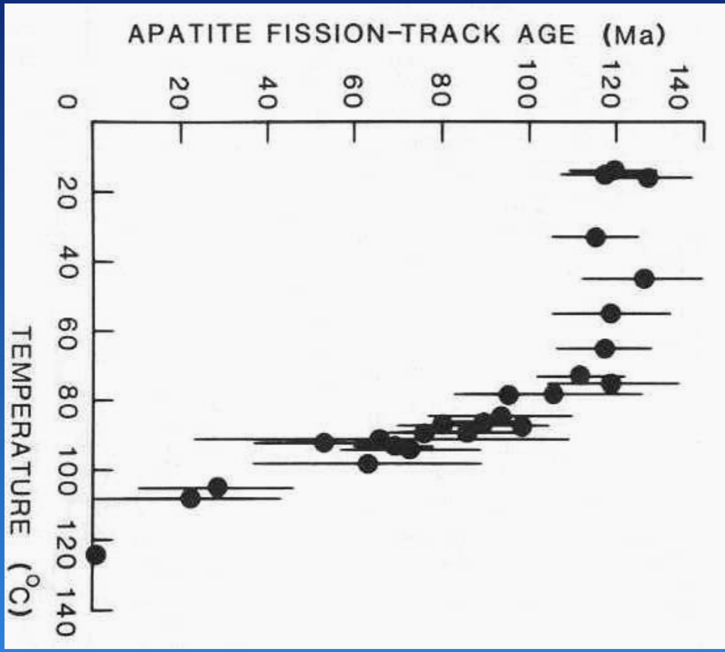


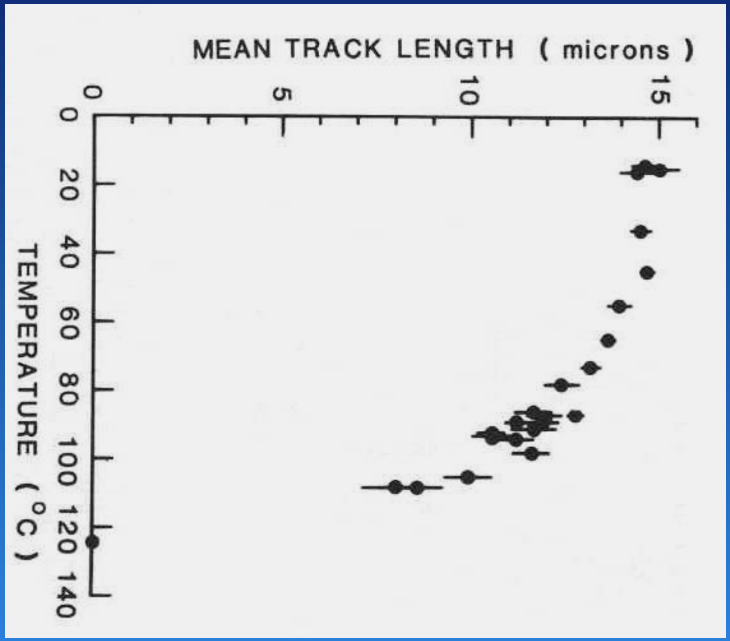
Maturation and Rank
MICROSCOPIC MATURITY PARAMETERS
CHEMICAL MATURITY PARAMETERS
Zones of HC Generation
Stages of Maturation
COAL RANK
Vitrinite Refl. (%Ro)
TAI*
TAI**
CONODONT ALTERATION INDEX (CAI)
FLUORESCENCE
COLOUR OF ALGINITE ***
λ MAX (NM)***
TASMAN. ALG. (Q)****
Solid Bitumin Refl. (%Rb)
Rock-Eval Tmax (°C)
MPI 1
MDR
20S/(20S+20R) C29 -Sterane
Dia C27 / Dia C27 + Reg C27 Sterane
DIAGENESIS
CATAGENESIS
METAGENESIS
Meta-morph.
PEAT
LIGNITE
SUB-BITUMIN. C B A
HIGH VOLATILE BITUMIN. C B A
MEDIUM VOLATILE BITUMIN.
LOW VOLATILE BITUMIN.
SEMI-ANTHRAC.
ANTHRAC.
META-ANTHRAC.
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.2
1.35
1.5
2.0
2.5
3.0
4.0
5.0
1 YELLOW
2 ORANGE
3 BROWN
4 BLACK
5 BLACK
1.5
2.3
2.5
2.8
3.0
3.5
3.7
4.0
1 YELLOW
2 LIGHT BROWN
3 BROWN
4 DARK BROWN
5 BLACK
GREENISH YELLOW
GOLDEN YELLOW
DULL YELLOW
ORANGE
RED
NON-FLUORESCENT
500
540
600
640
680
0.5
0.7
1.0
1.3
1.5
1.8
0.2
0.5
1.0
1.5
1.75
2.0
2.5
400
425
435
450
475
500
550
0.2
0.52
0.86
1.38
2.2
1.45
1.02
0.0
2.8
5.6
8.2
0.1
0.25
0.5
0.6
0.2
0.65
0.8
Biogenic Methane, Heavy Oil and Early Condensate.
Oil, Wet Gas and Condensate
Oil Window
Major Thermogenic Gas Generation
Wet gas
Dry Gas
Start of Thermogenic Gas Generation
Dry Gas
Mukhopadhyay (1994)

Geothermal Gradient in a Well



Otway Basin trend:



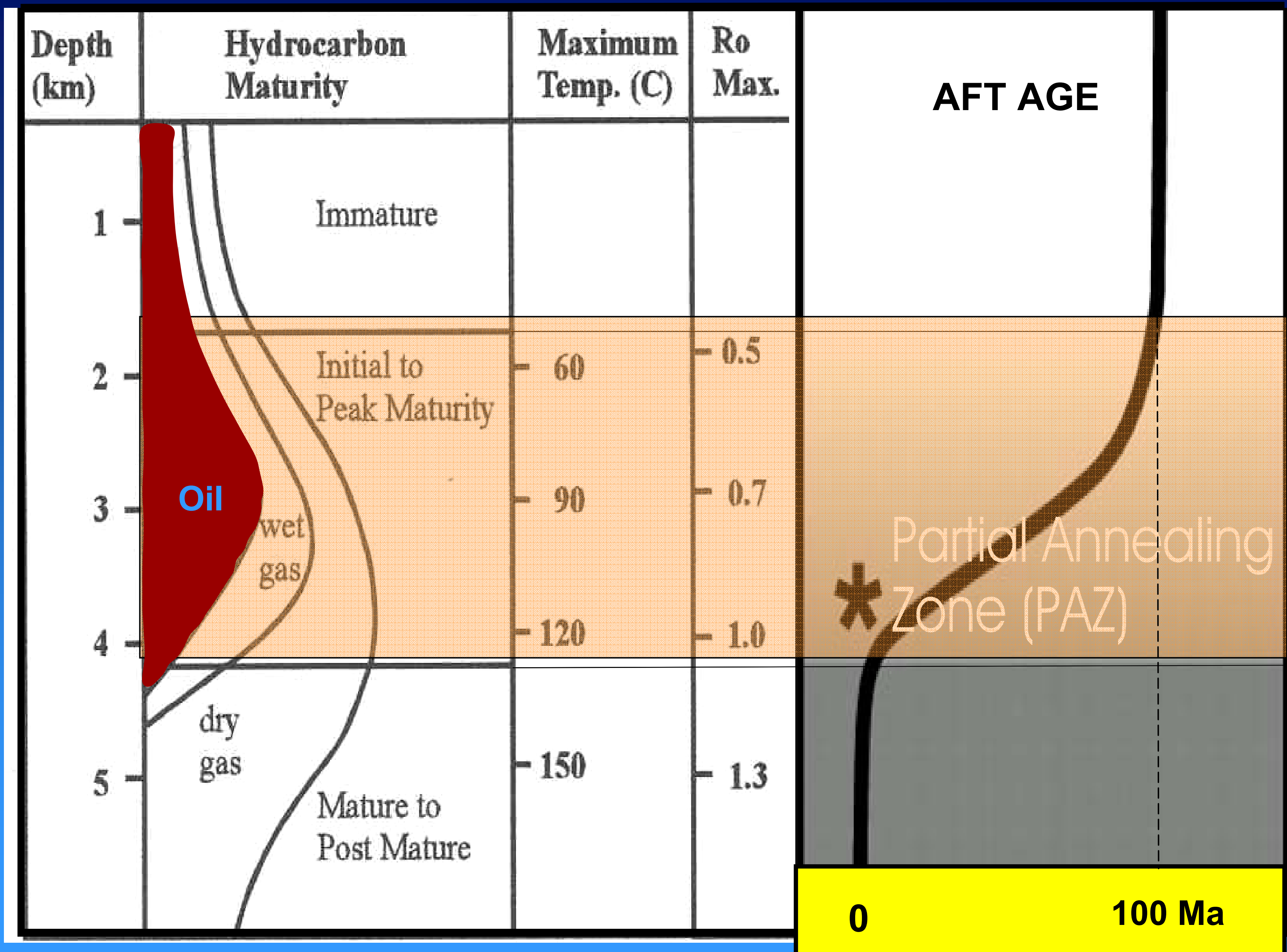


(Green et al. 1988)

Within Otway Basin (SE Austratia) wells:

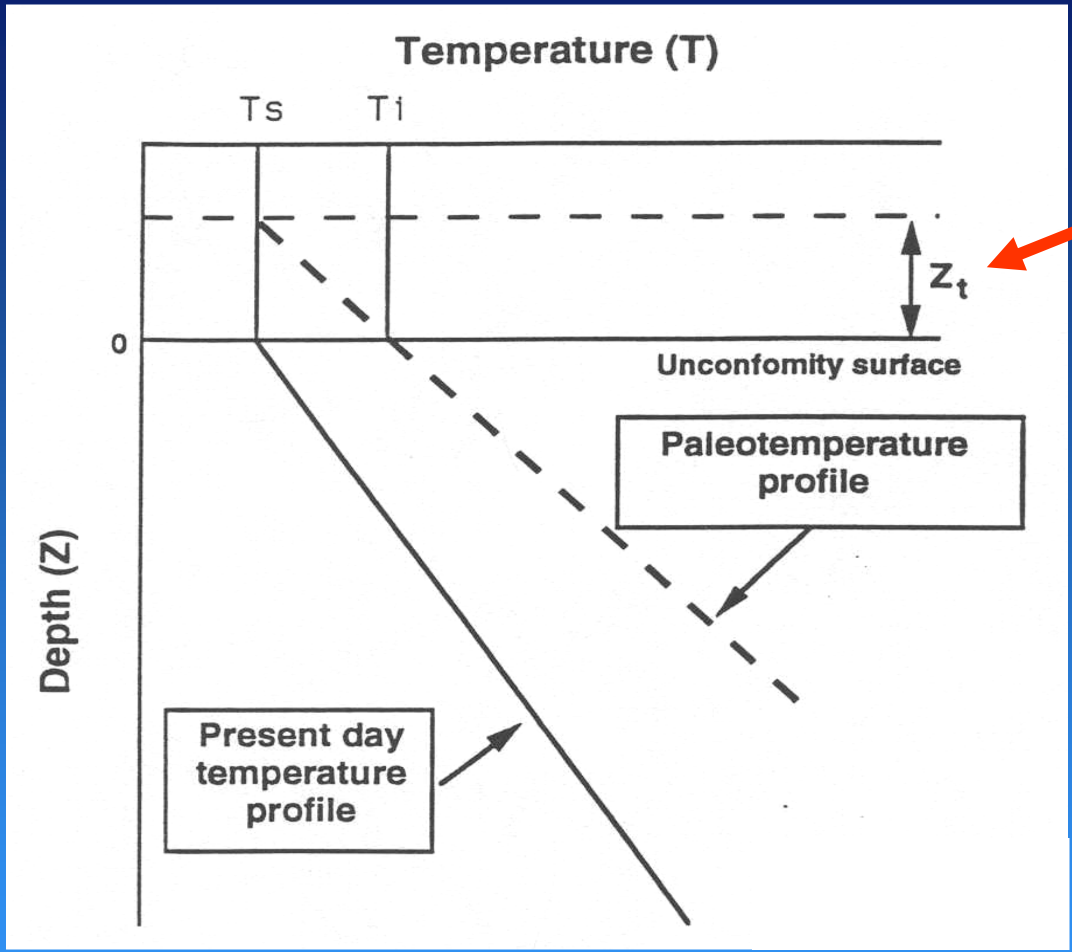
Apatite FT ages decrease with increasing T; 0 ages at T > 110° C.

Mean TL decreases with increasing T; segmentation begins at < 9 µm, fall rapidly to 0 at ca. 110 °C.



Depth (km)
Hydrocarbon Maturity
Maximum Temp. (C)
Ro Max.
AFT AGE
1
2
3
4
5
Immature
Initial to Peak Maturity
Oil
wet gas
dry gas
Mature to Post Mature
60
90
120
150
0.5
0.7
1.0
1.3
Partial Annealing Zone (PAZ)
0
100 Ma

Estimation of Removed Section



eroded

e.g. from AFT and Vitrinite Reflectance (R_o)

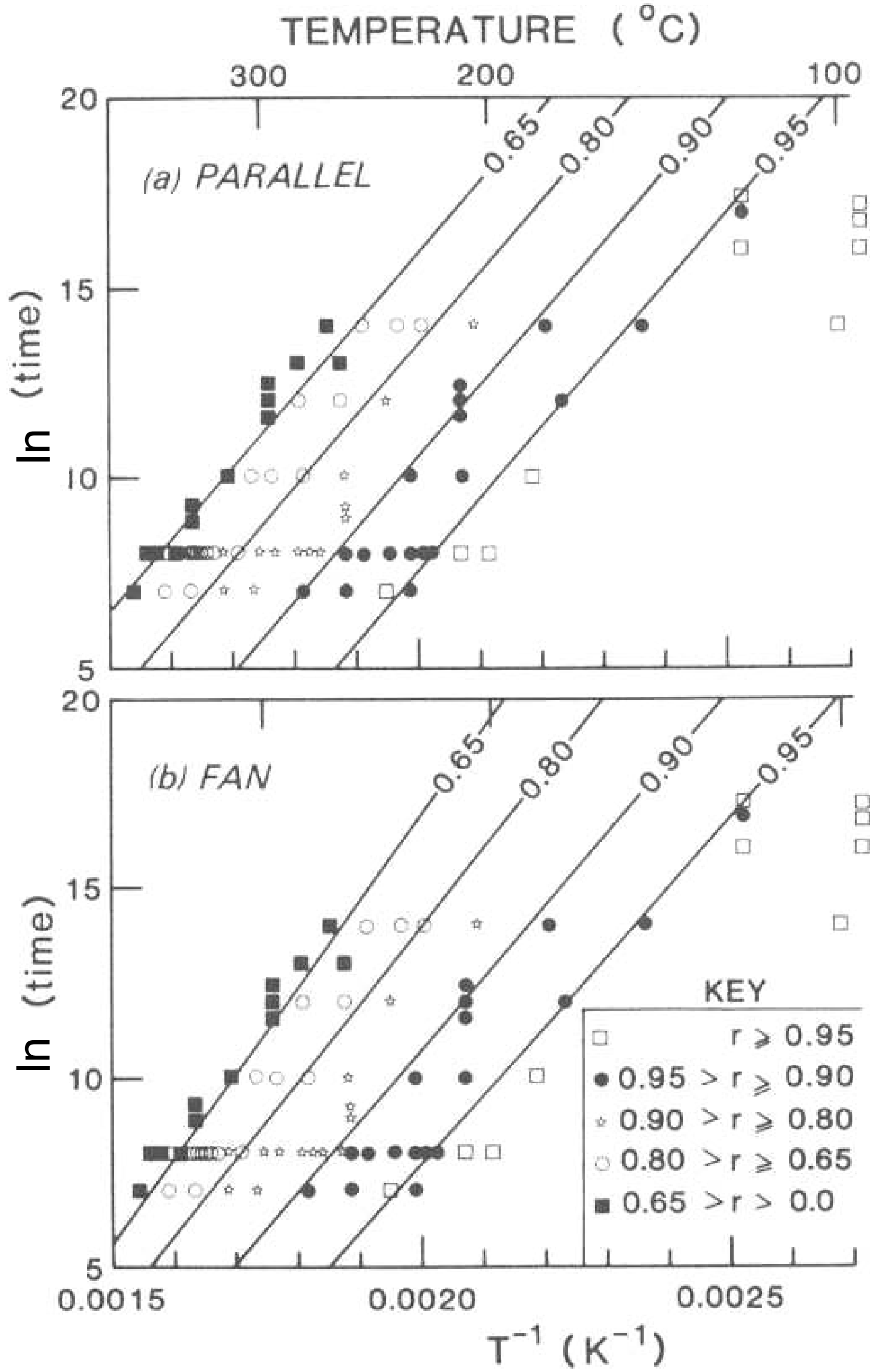
Green and Duddy (1993)

Apatite annealing

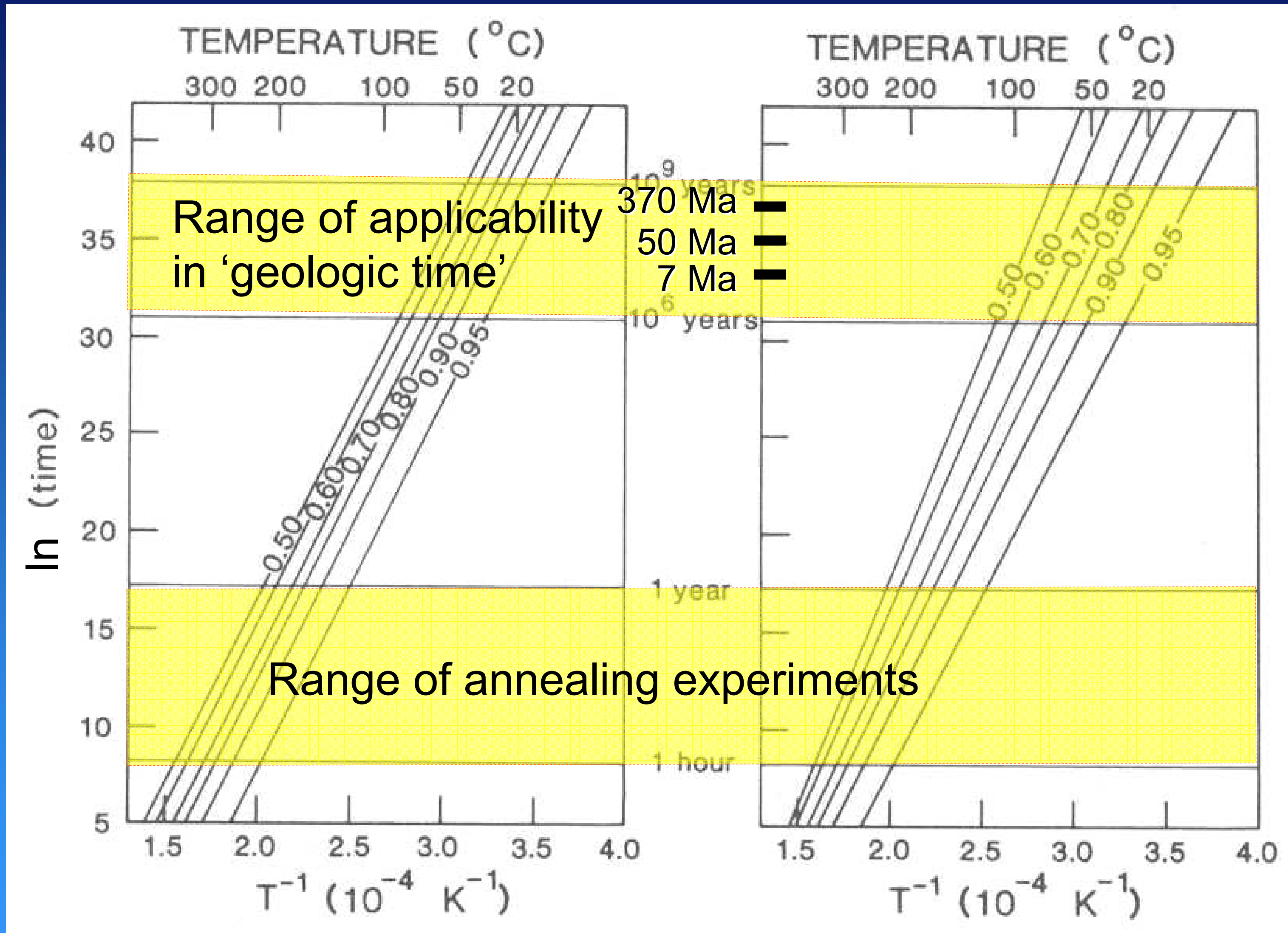
Laboratory annealing data of Green et al. (1986) extrapolated to geologic time

Like baking a cake in half the time at double the temperature ……..

(Laslett et al. 1987)

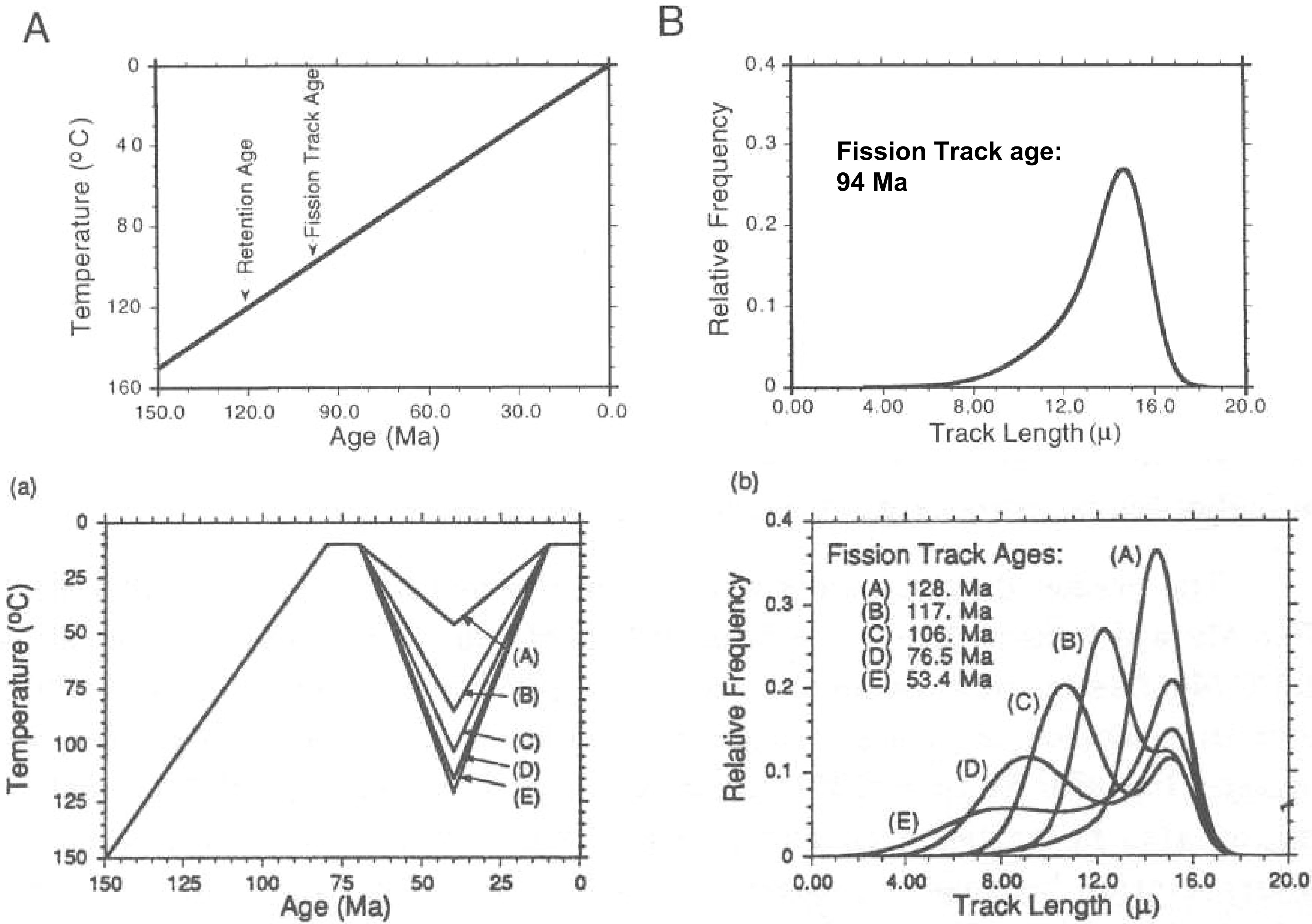


Apatite FT thermal models:

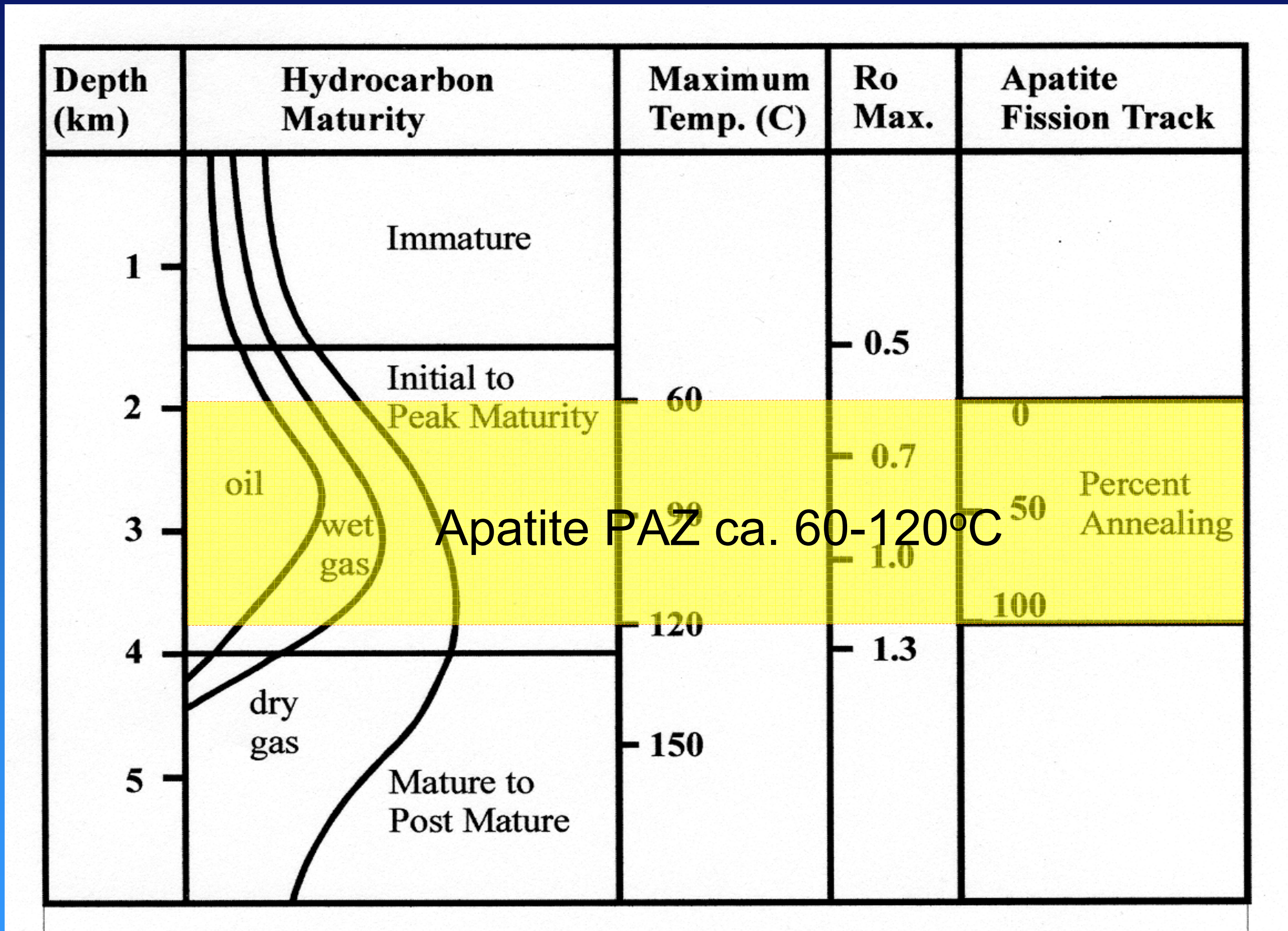


- predict annealing behaviour over geologic time

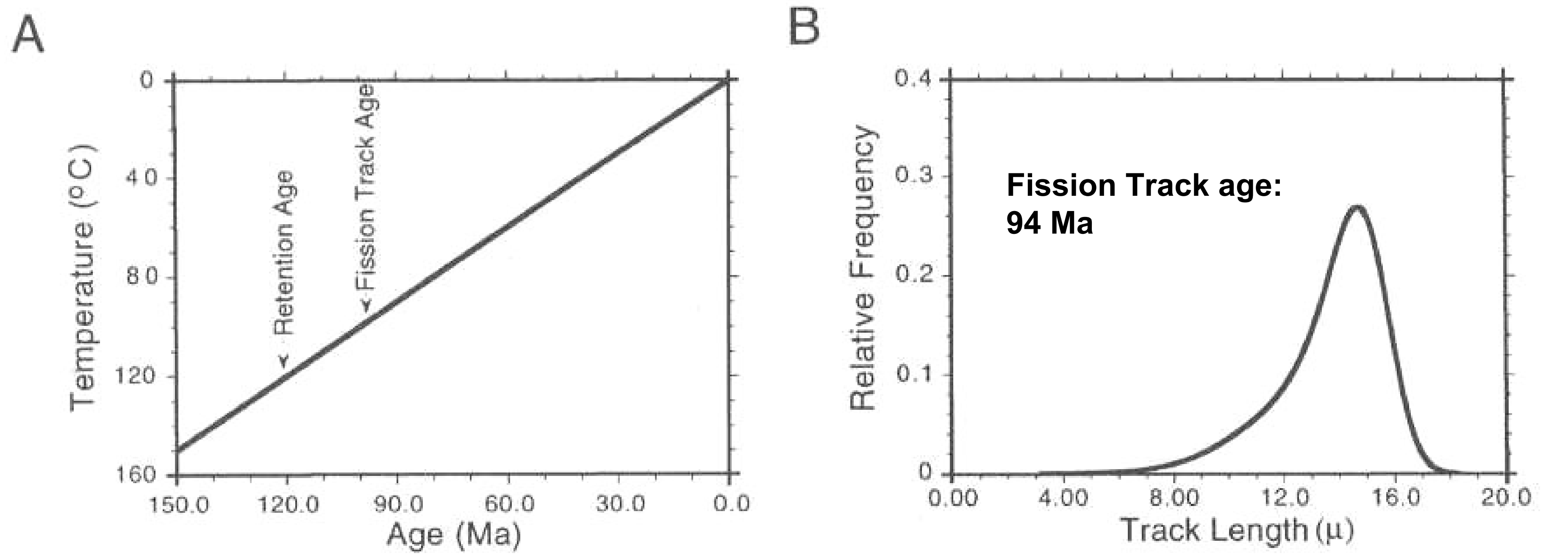
(Laslett et al. 1987)

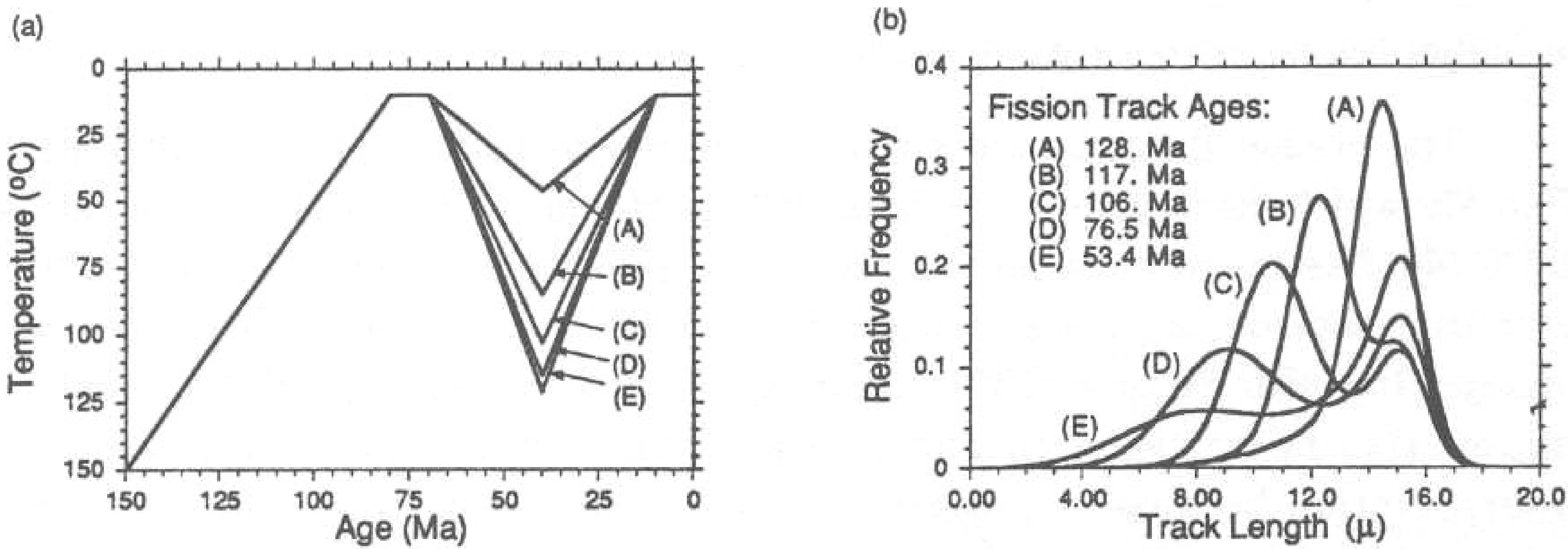


(Willett, 1992; 2000)



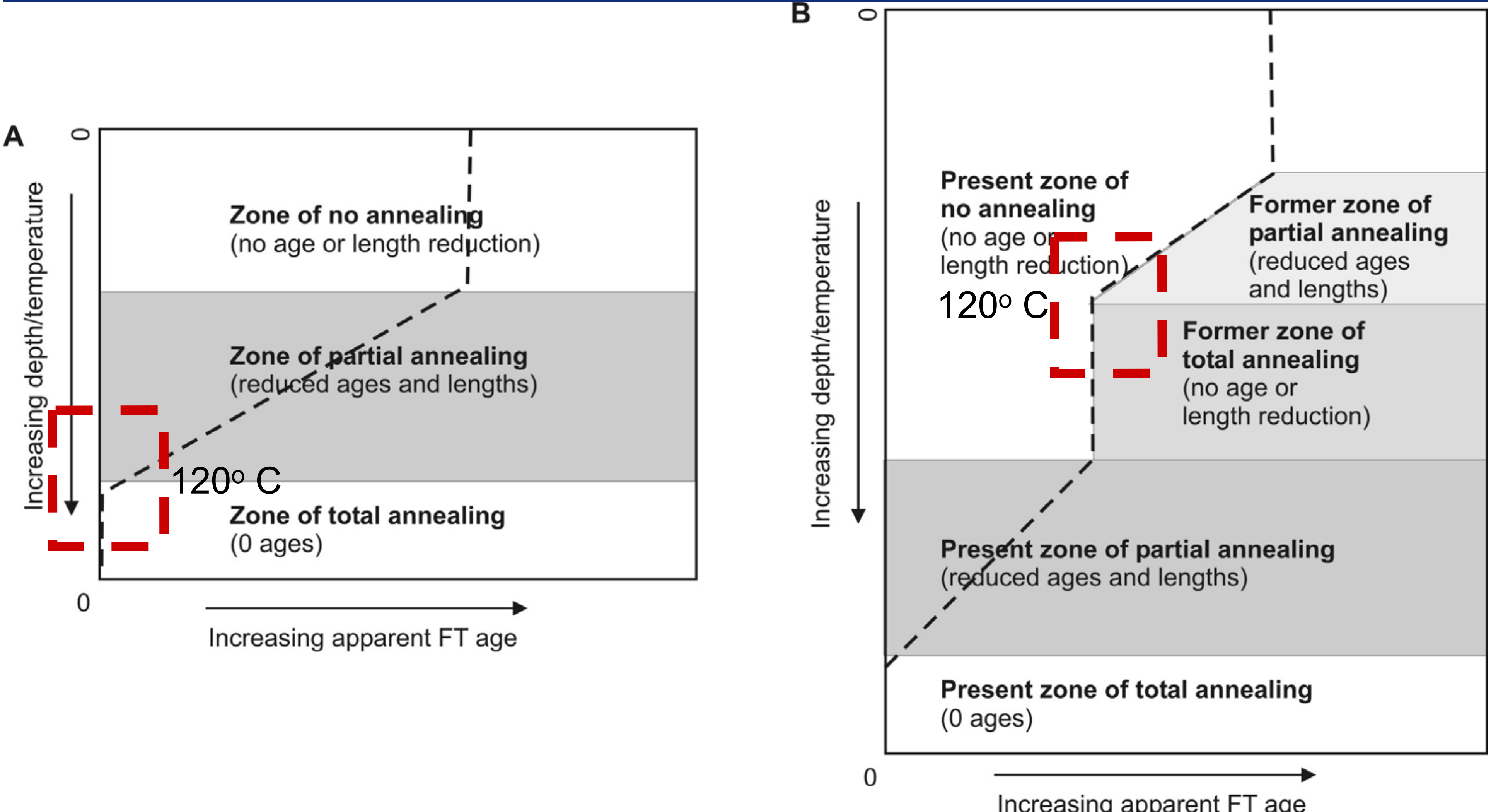
(Gleadow et al. 1983)





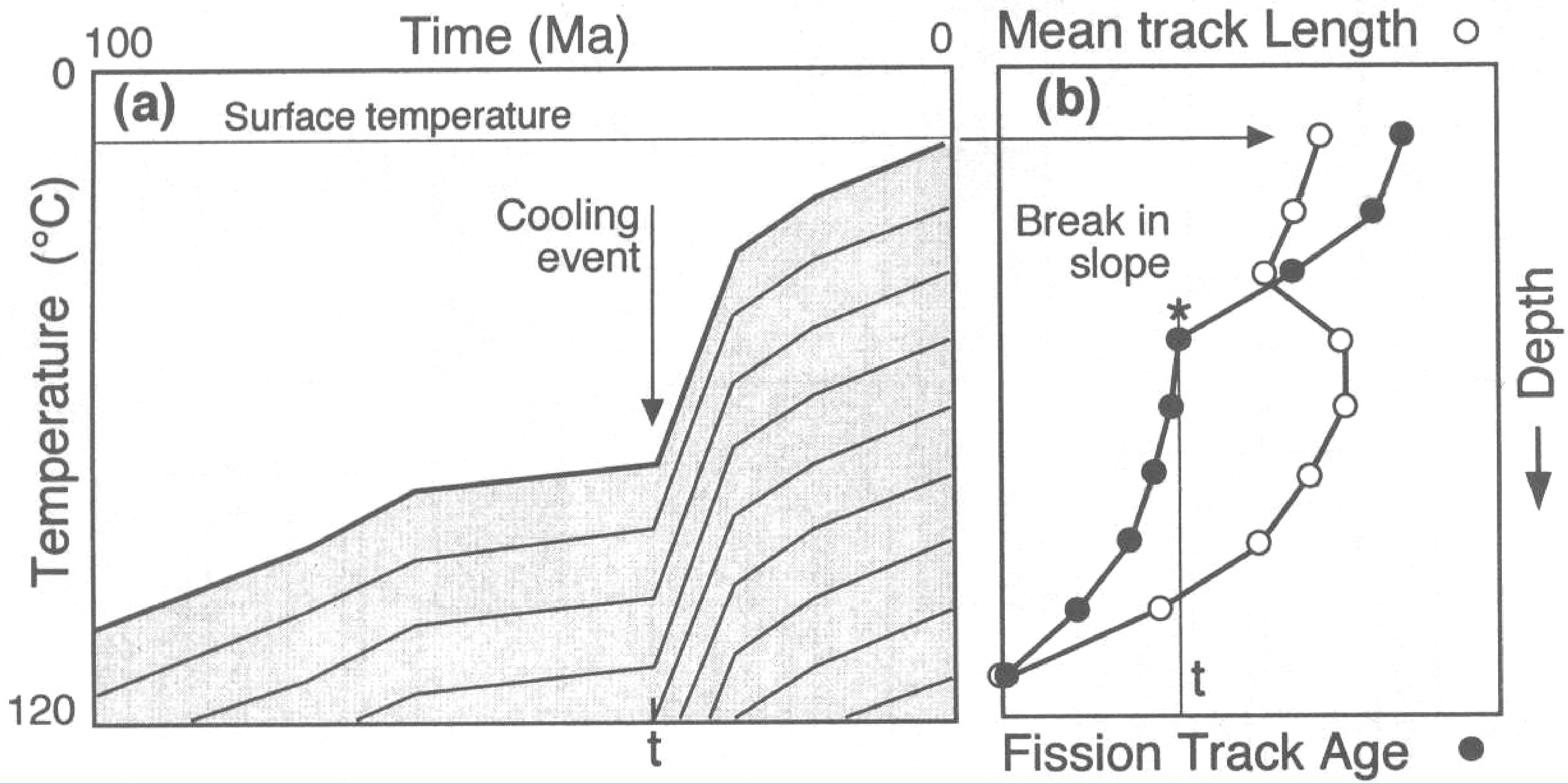
(Willett, 1992; 1997)

Partial Annealing Zone (PAZ)



(after Naeser, 1979)

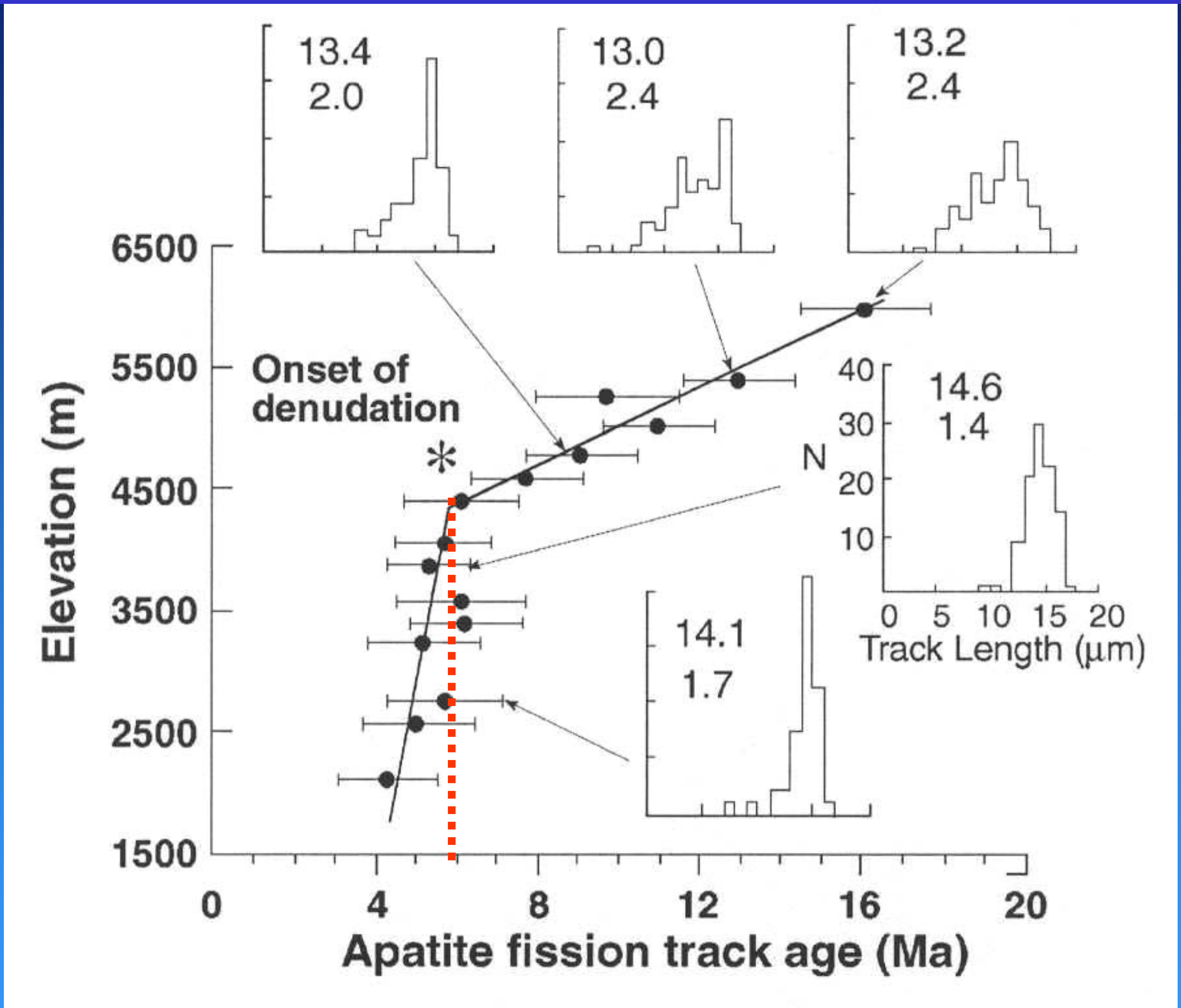
Modelling a rapidly exhumed PAZ:



(Gleadow et al. 2002)

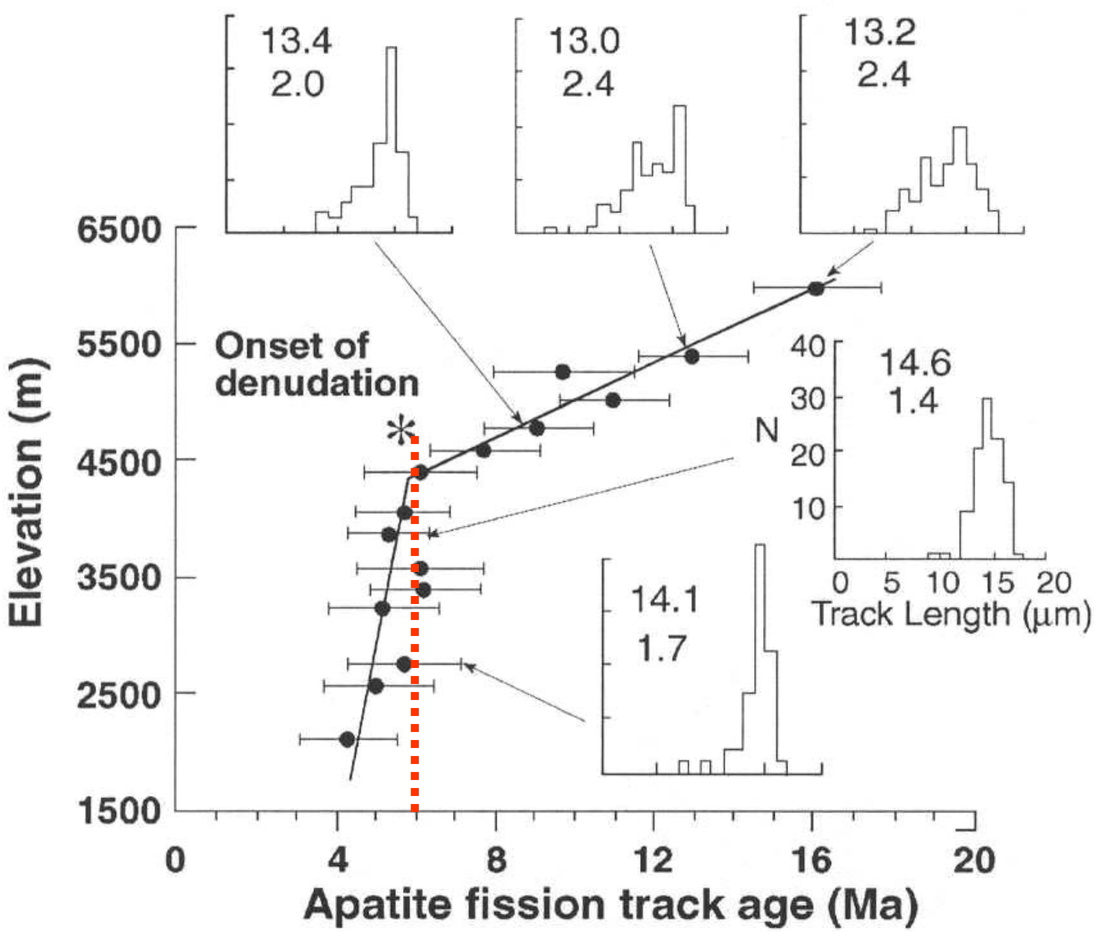
Exhumed PAZ 1: Denali Fault, Alaska Range:

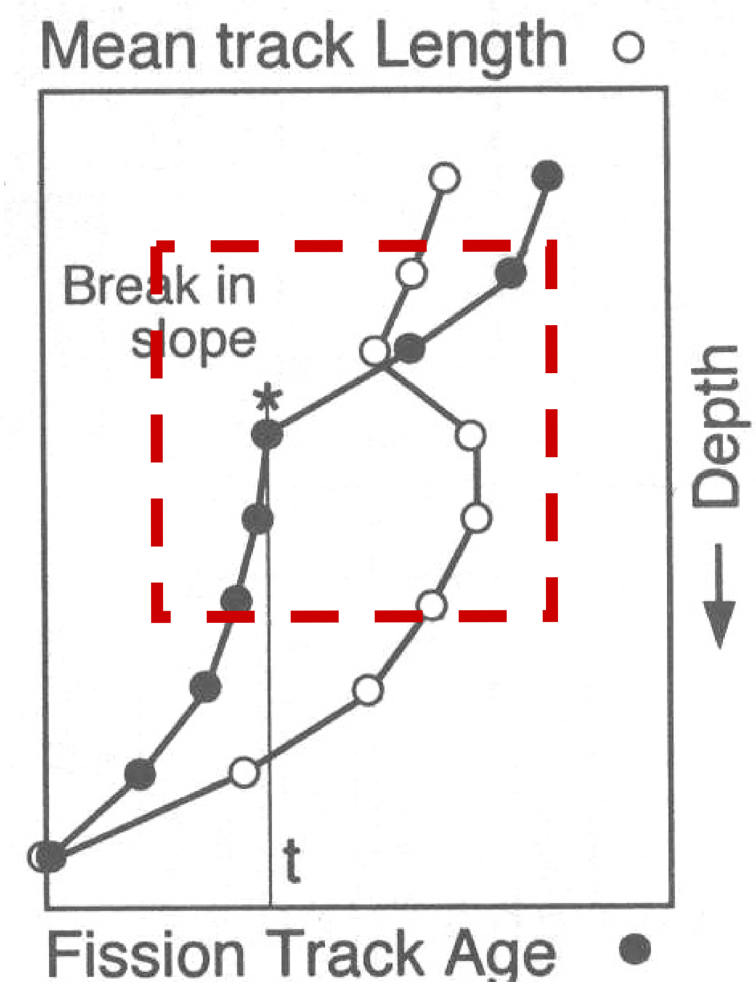
(Fitzgerald et al. 1995)



- Break in slope = former base of PAZ, 0 ages (ca. 120° C).
- Long TL indicate rapid cooling through PAZ, initiated of ca. 6 Ma.

Exhumed PAZ Denali Fault:

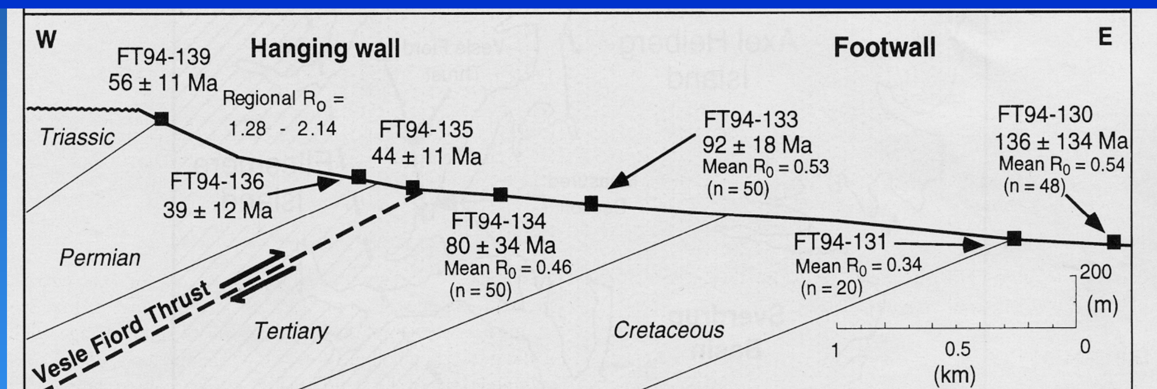




(Fitzgerald et al. 1995)

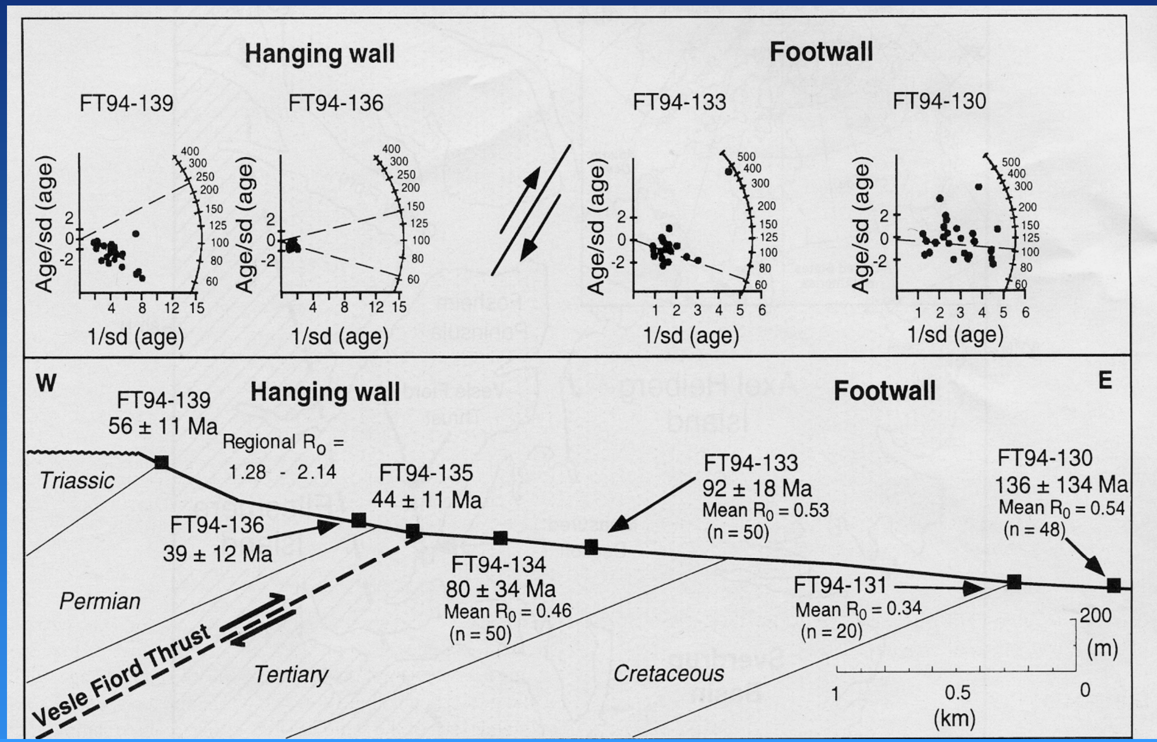
(Gleadow et al. 2002)

Dating a Thrust Fault



Arne, Zentilli, Grist, Collins
1998 CJES

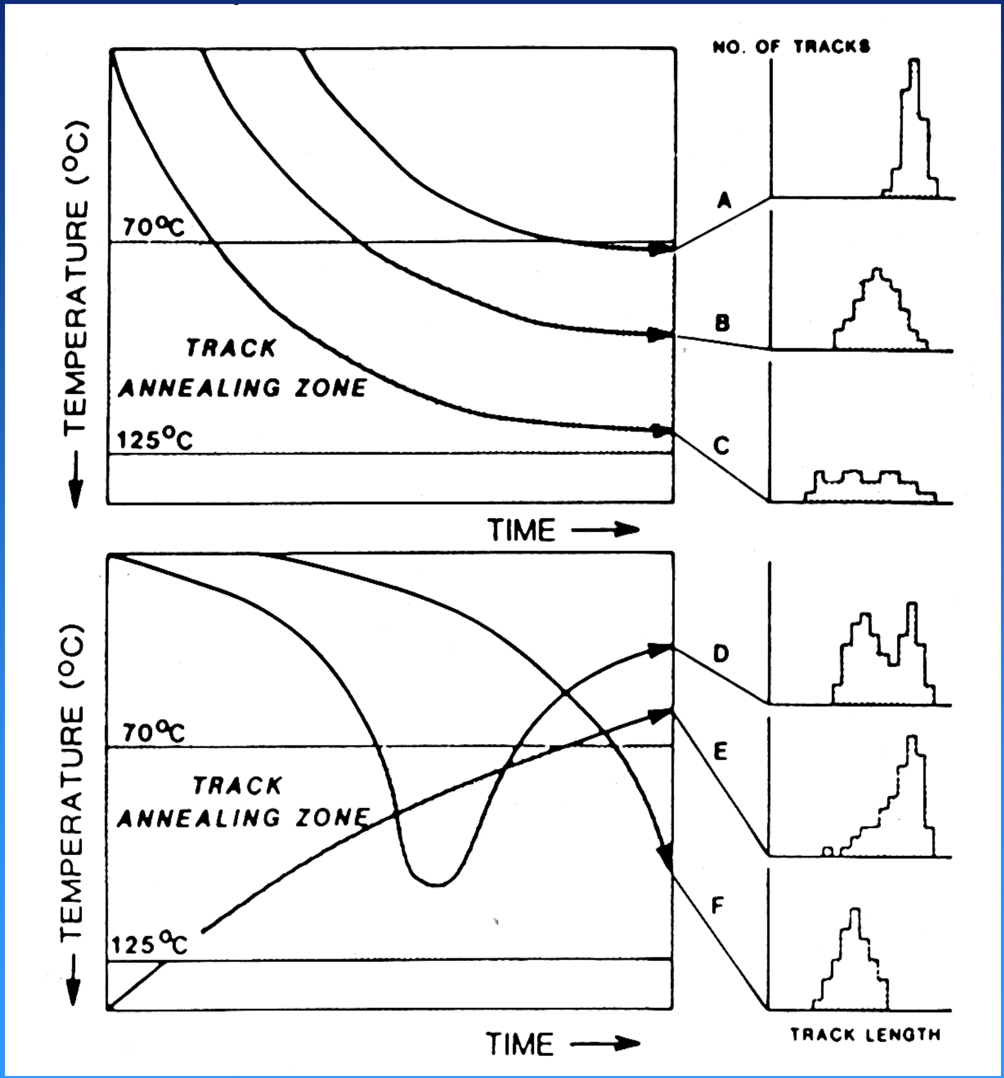
Dating a Thrust Fault



Arne, Zentilli, Grist, Collins
1998 CJES

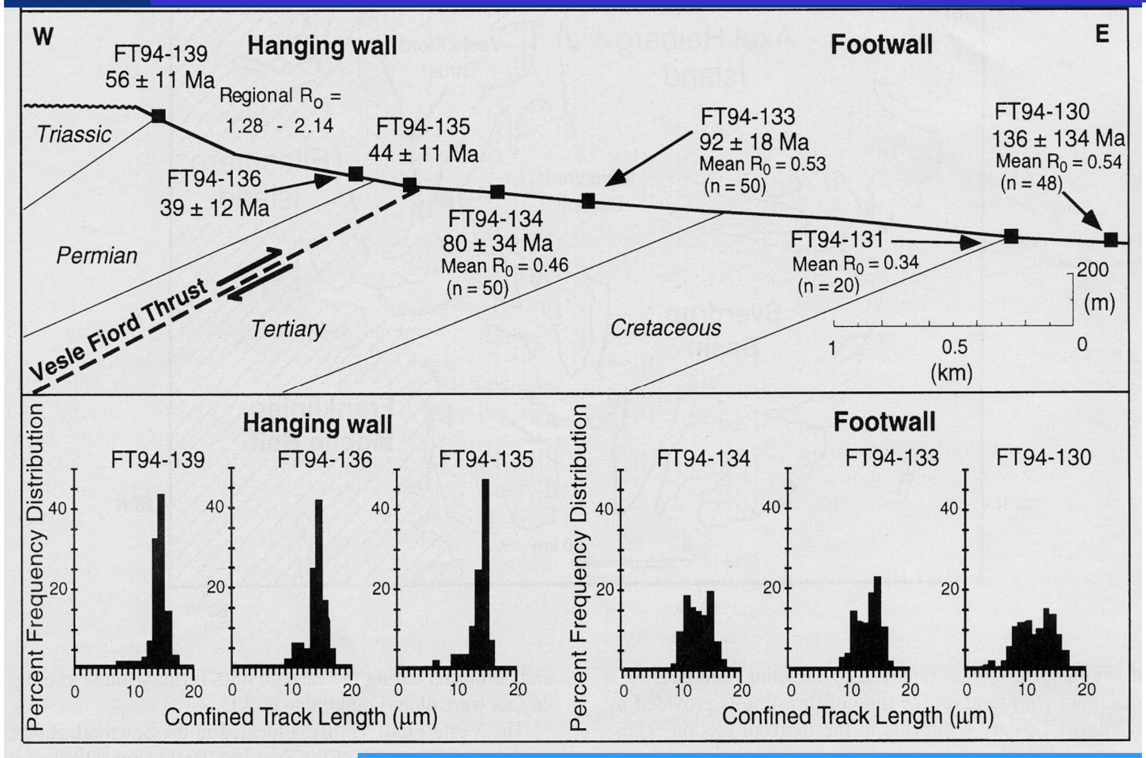
TL thermochronology

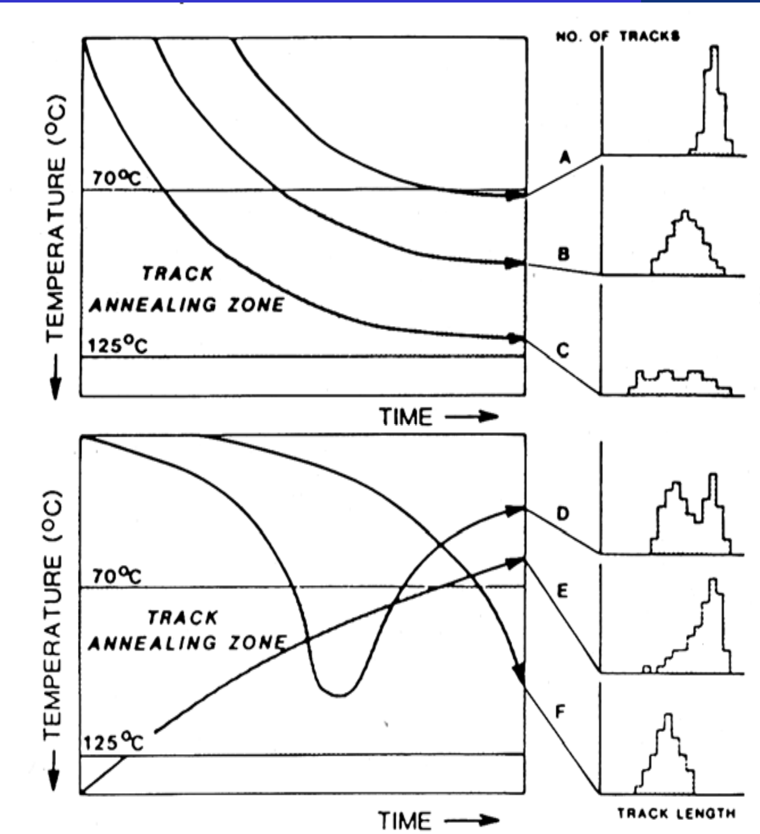
Length distributions are indicative of thermal history



(Gleadow et al. 1983)

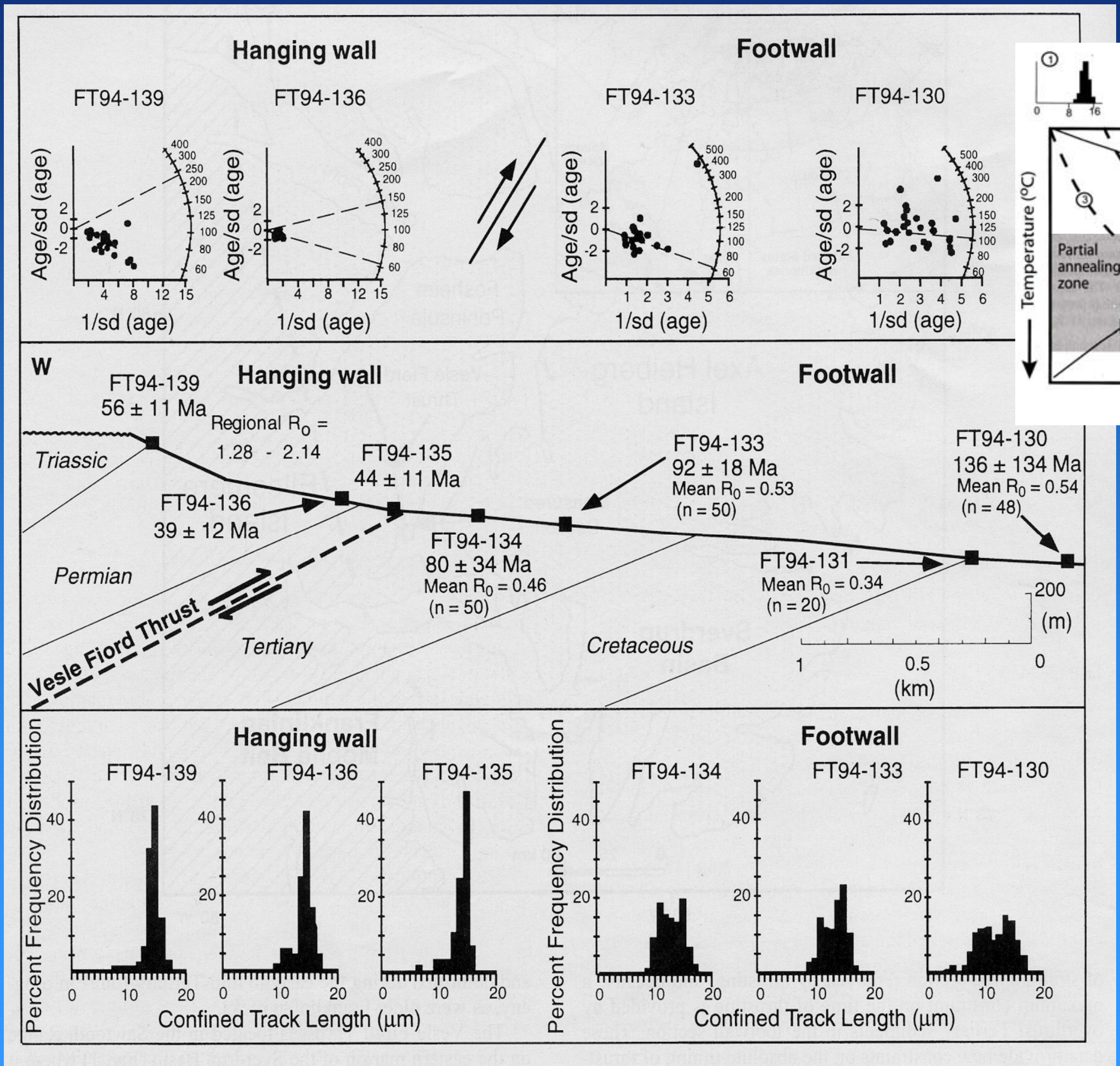
Dating a Thrust Fault

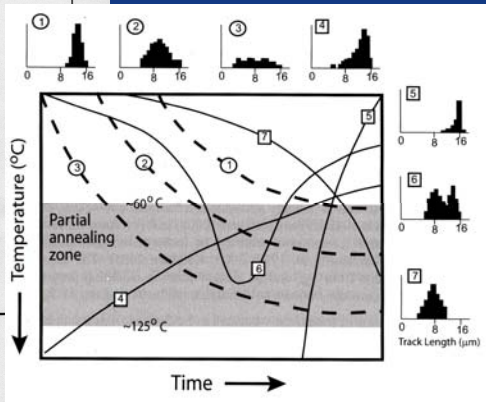


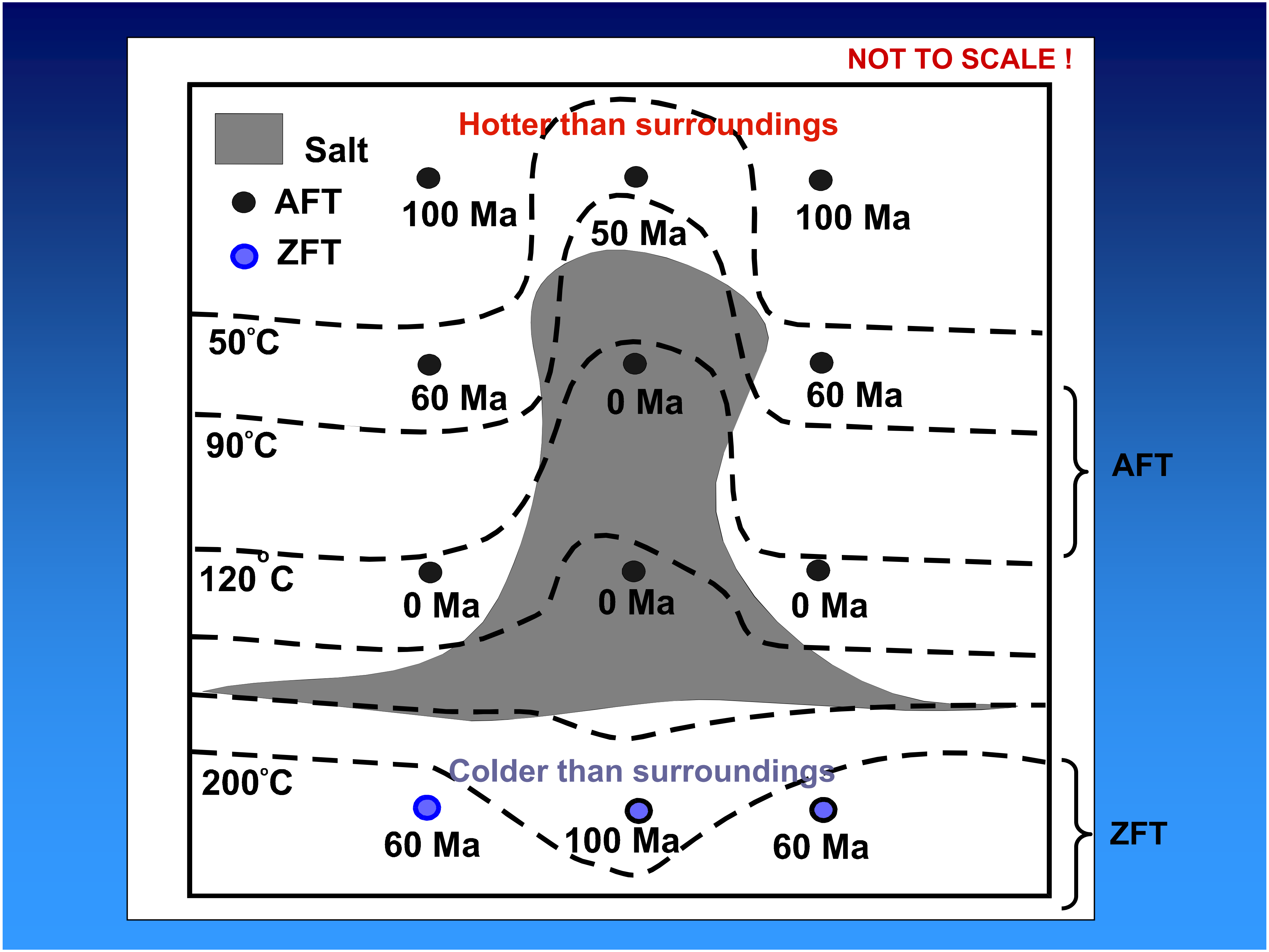


Arne, Zentilli, Grist, Collins
1998 CJES

Dating a Thrust Fault

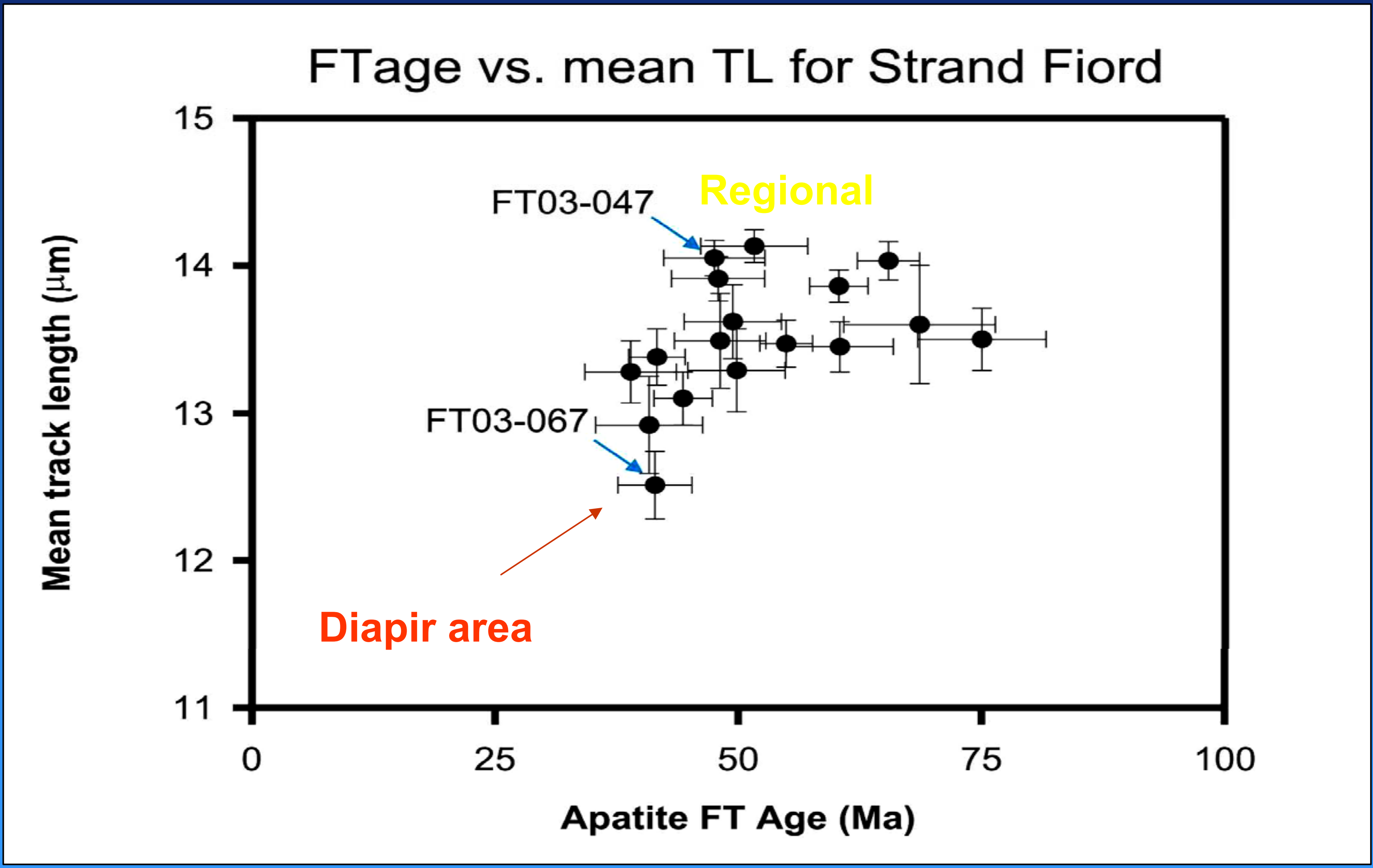






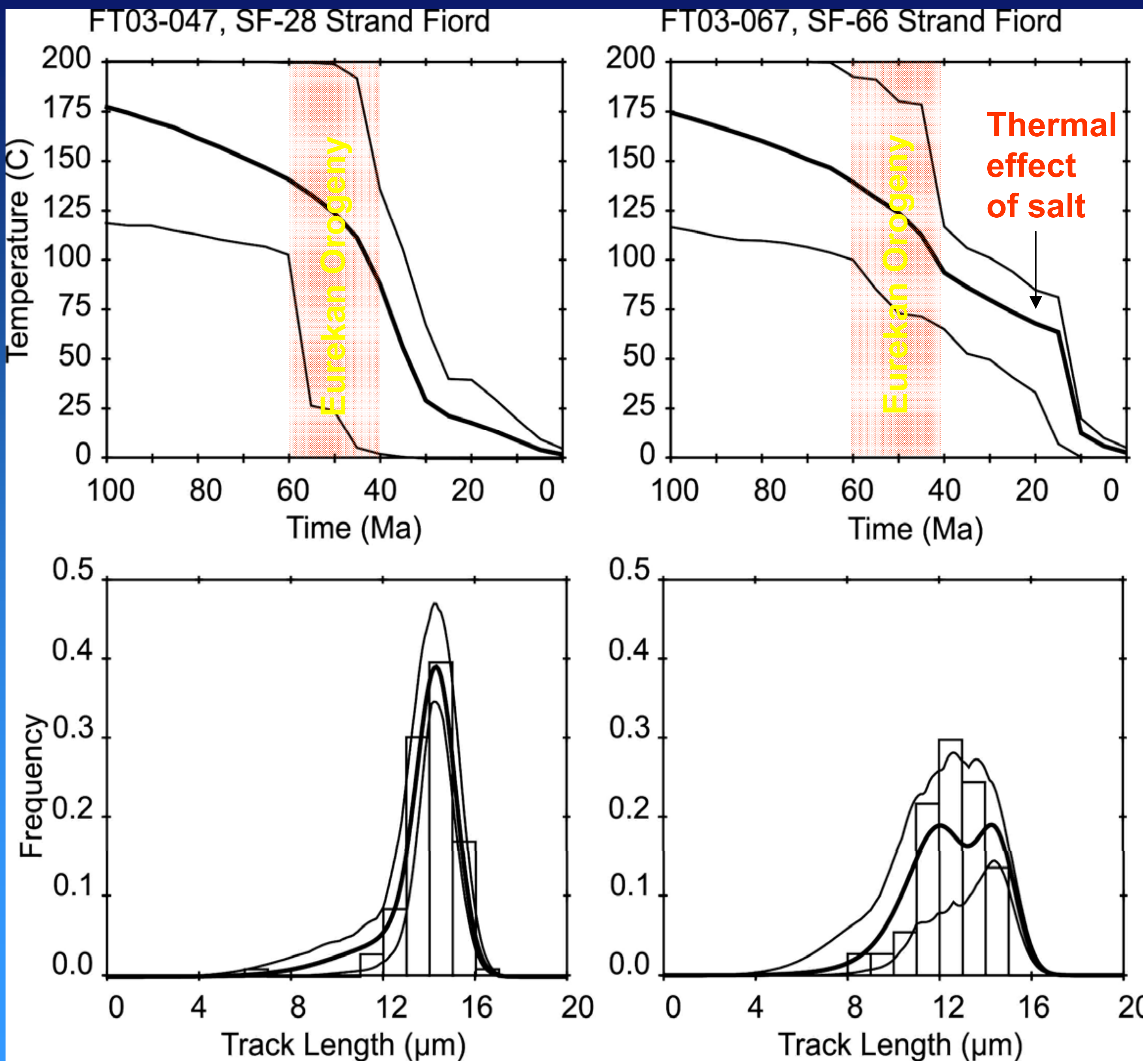
NOT TO SCALE !
Salt
AFT
ZFT
Hotter than surroundings
100 Ma
50 Ma
100 Ma
50°C
60 Ma
0 Ma
60 Ma
90°C
120°C
0 Ma
0 Ma
0 Ma
200°C
Colder than surroundings
60 Ma
100 Ma
60 Ma
AFT
ZFT

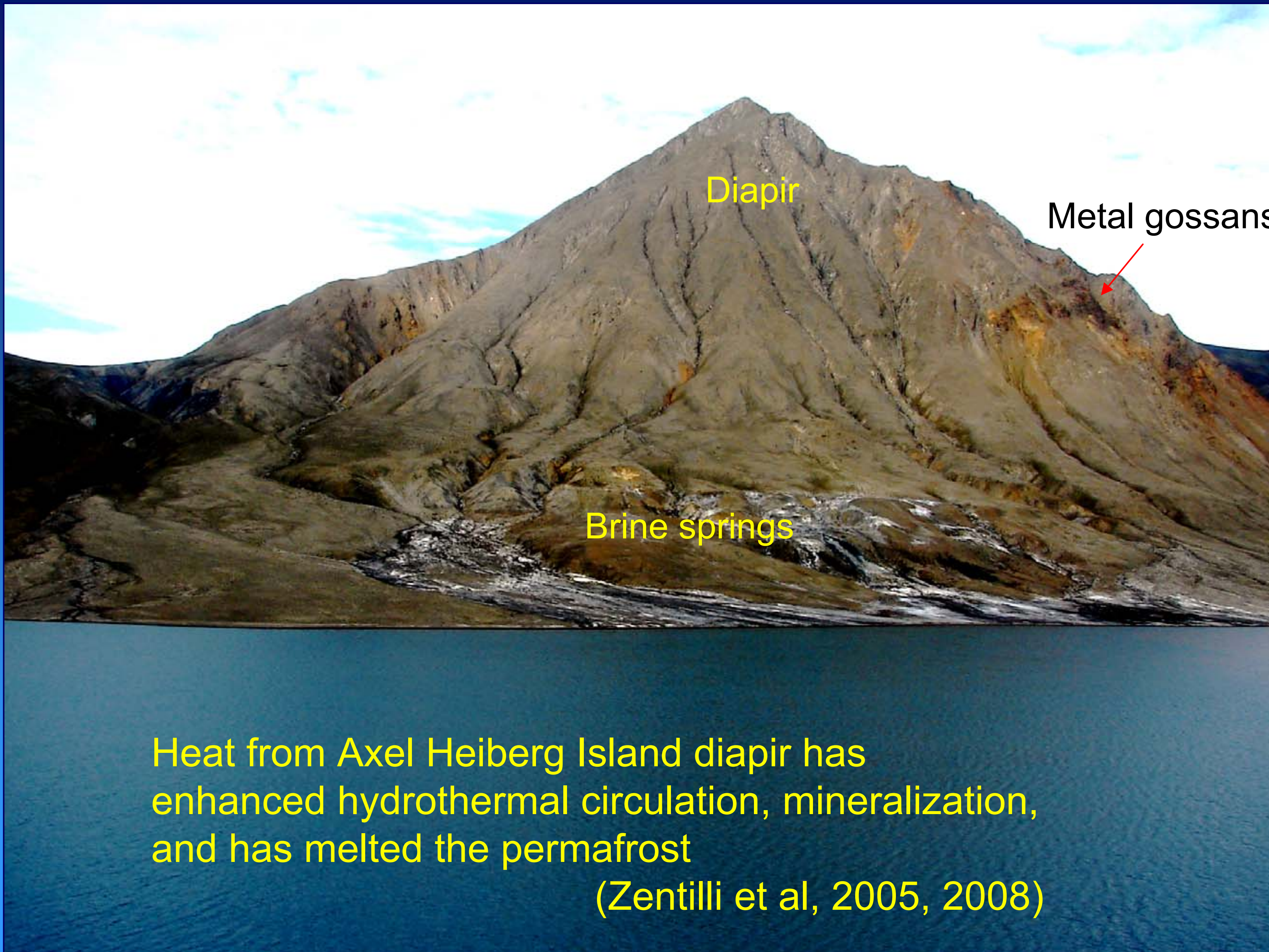
AFT detects heat focussed by salt diapir



Regional

Diapir area



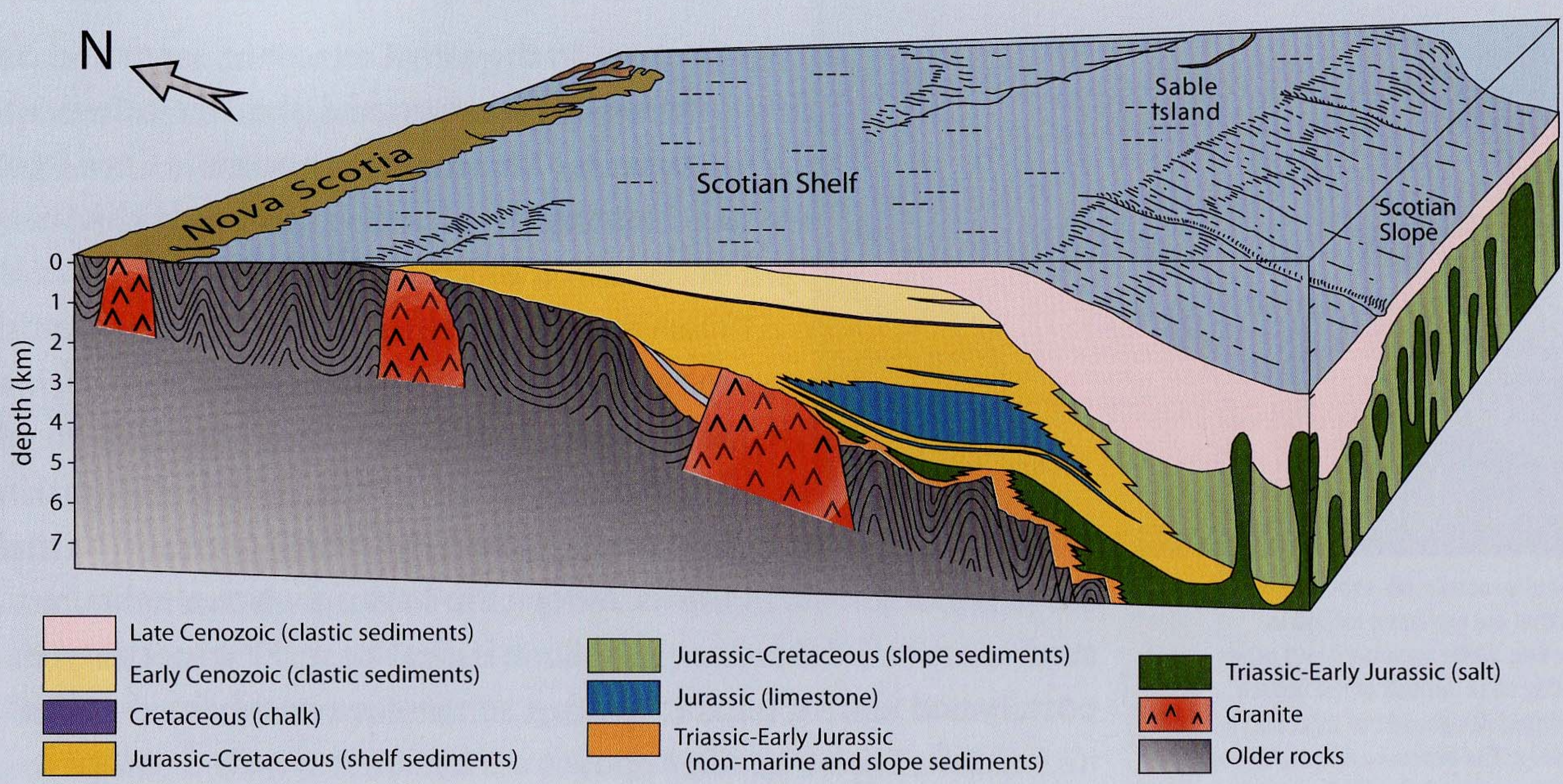


Heat from Axel Heiberg Island diapir has enhanced hydrothermal circulation, mineralization, and has melted the permafrost

(Zentilli et al, 2005, 2008)

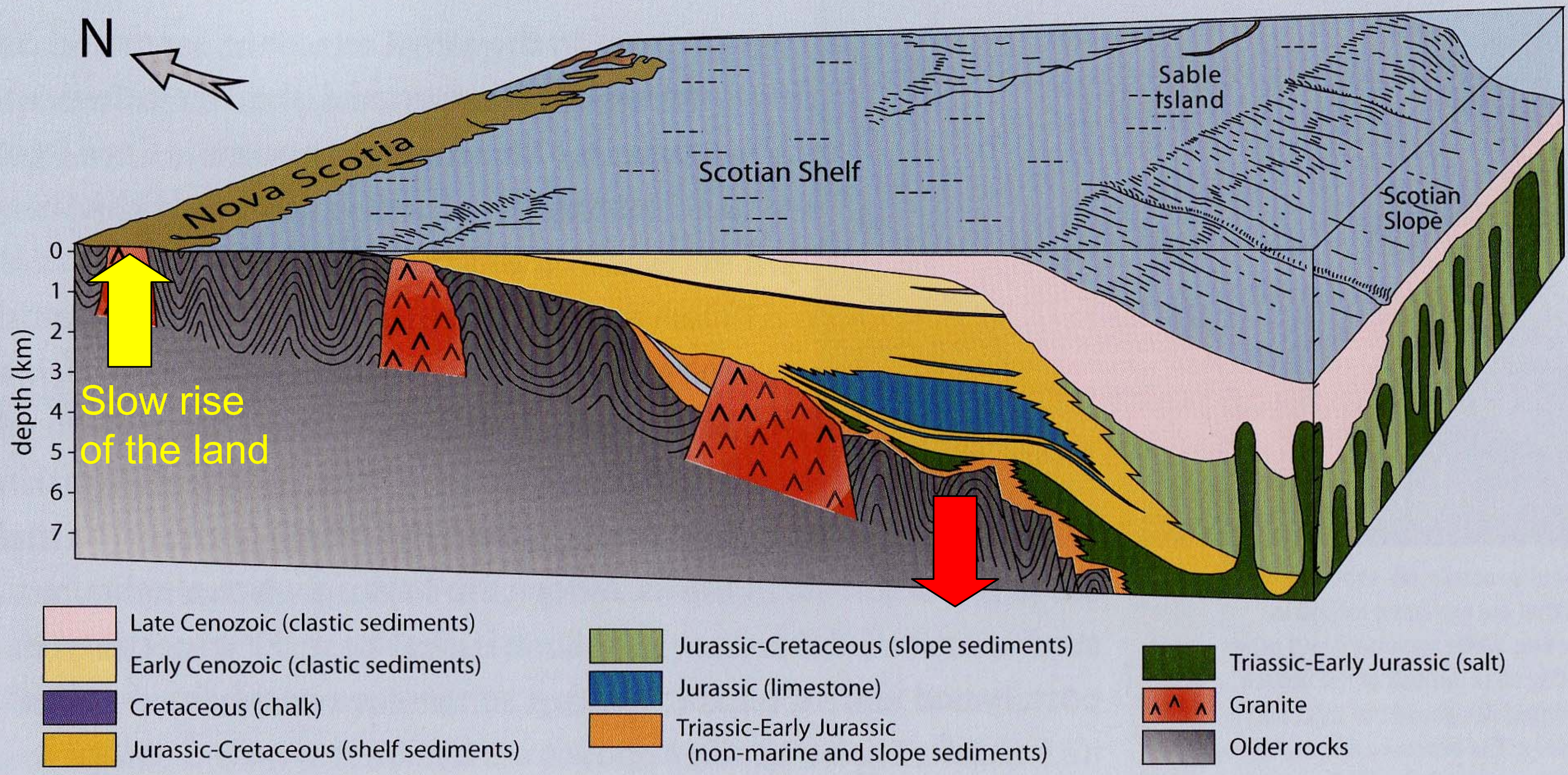
AFT Detects Inversion in Scotian Basin

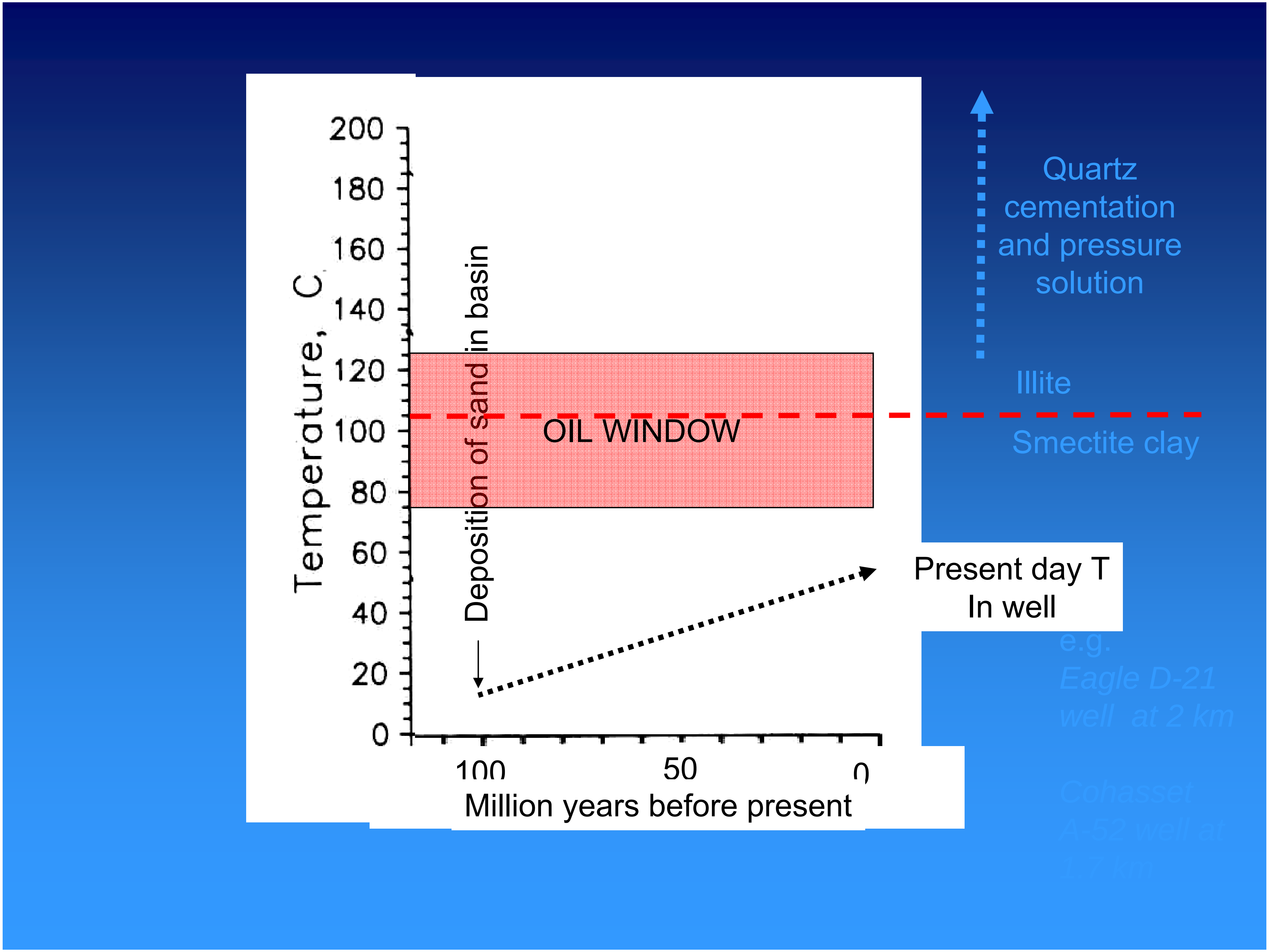
(Grist, A.M., & Zentilli, M. (2003). Can. Journal of Earth Sciences, 40, No. 9, 1279-1297)

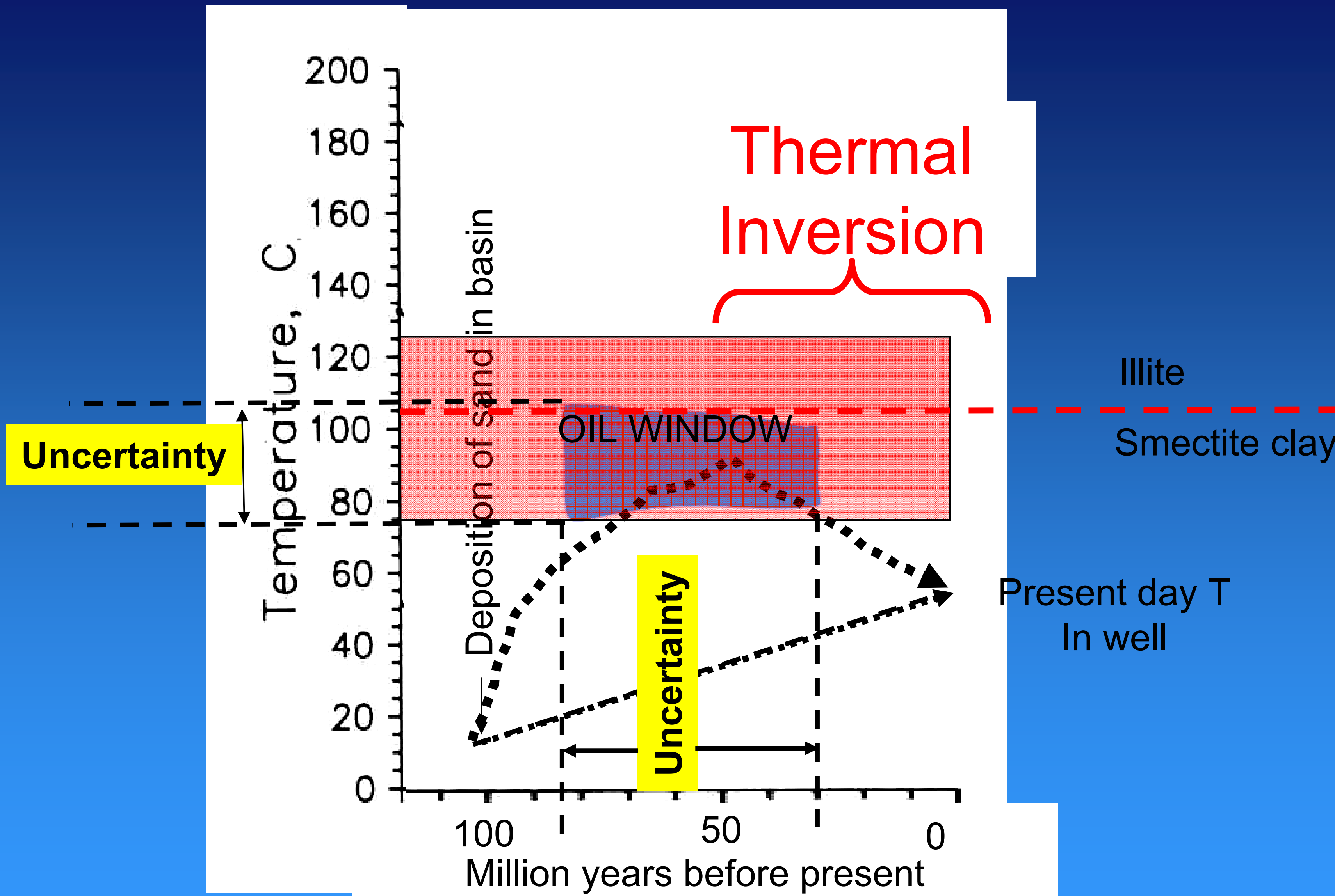


Assumption:
Margin slowly sinking since Triassic - Jurassic rifting

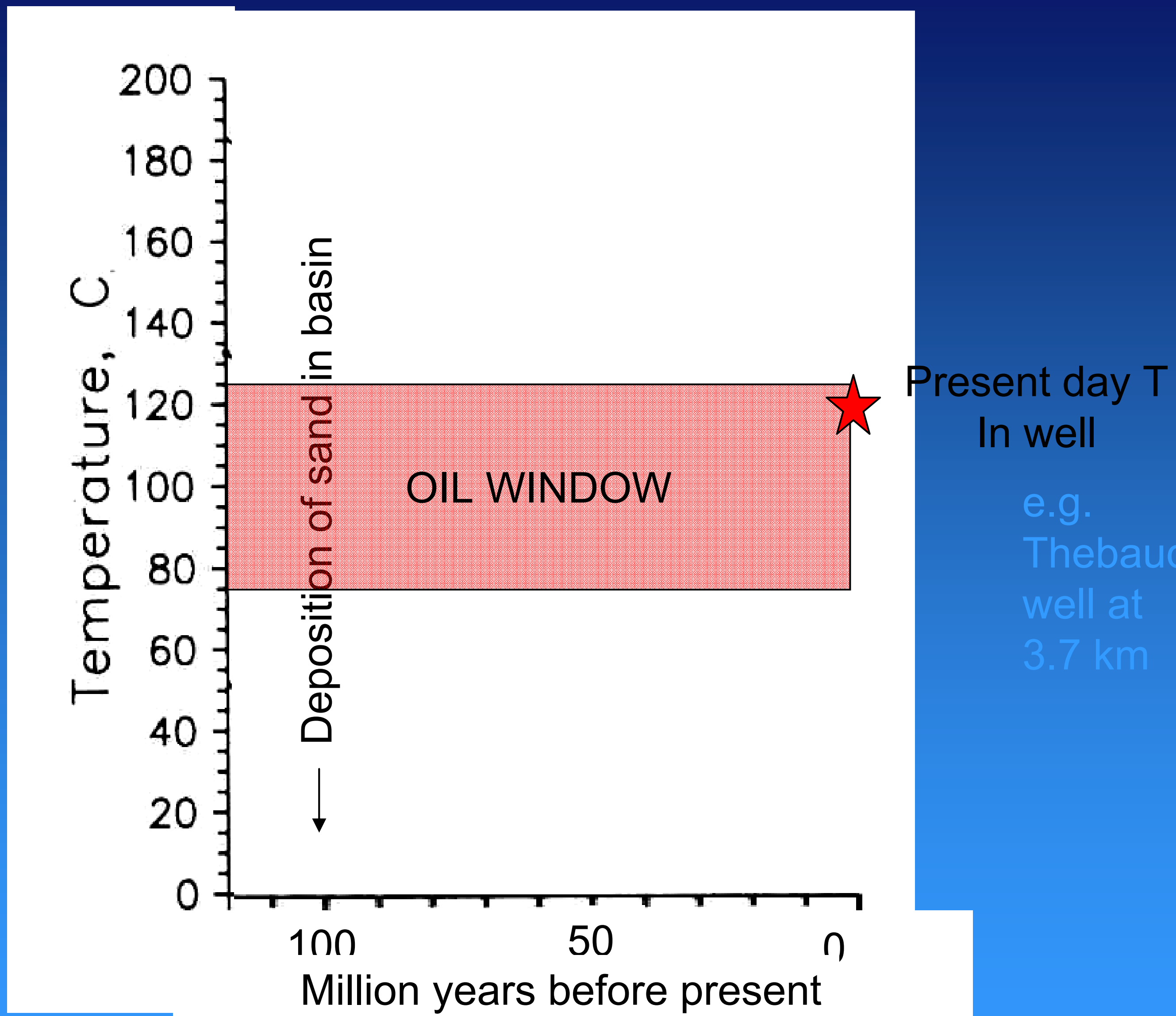
AGS The Last Billion Years



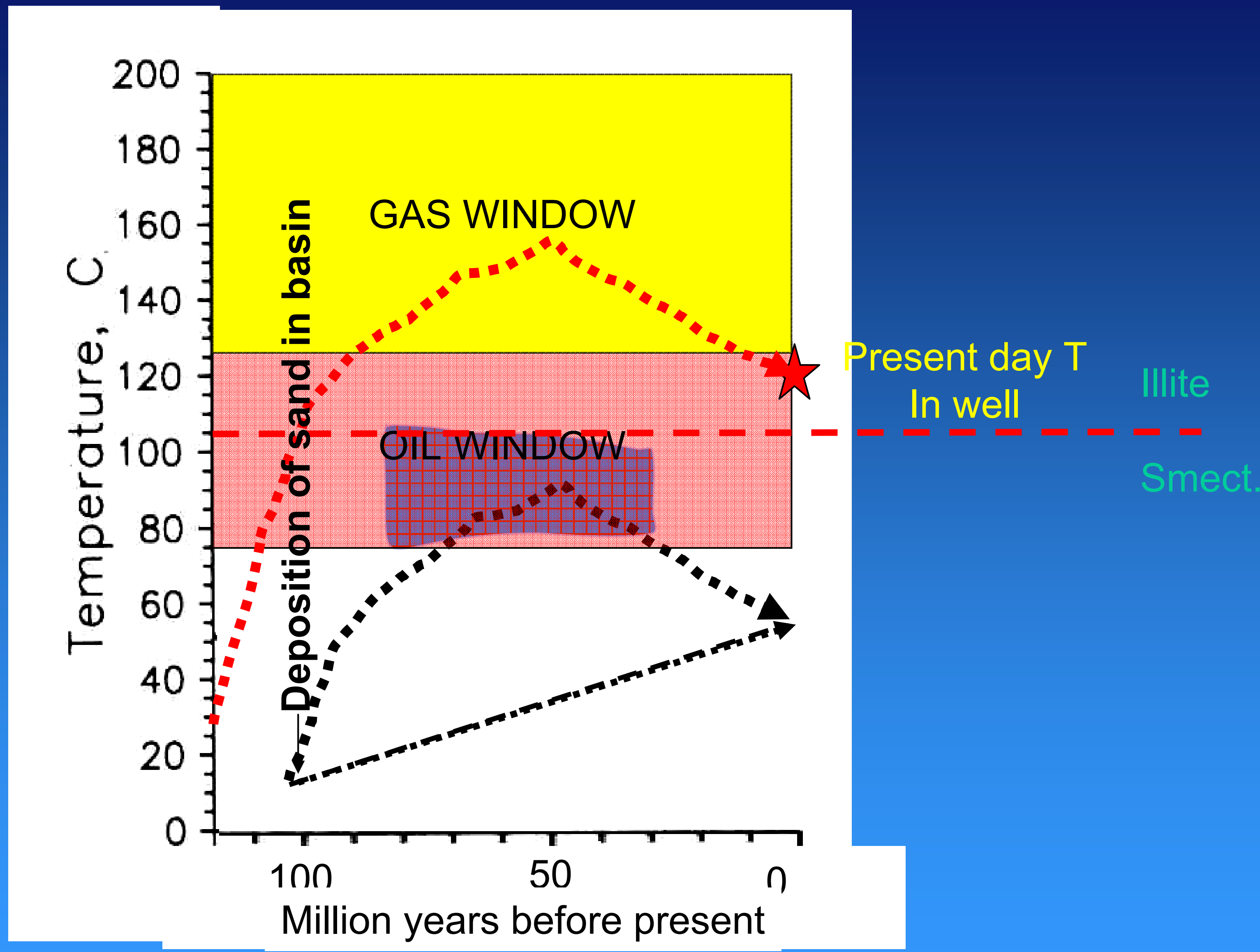

Temperature, C
200
180
160
140
120
100
80
60
40
20
0
100
50
0
Million years before present
Deposition of sand in basin
OIL WINDOW
Present day T
In well
Quartz
cementation
and pressure
solution
Illite
Smectite clay
e.g.
Eagle D-21
well at 2 km
Cohasset
A-52 well at
1.7 km



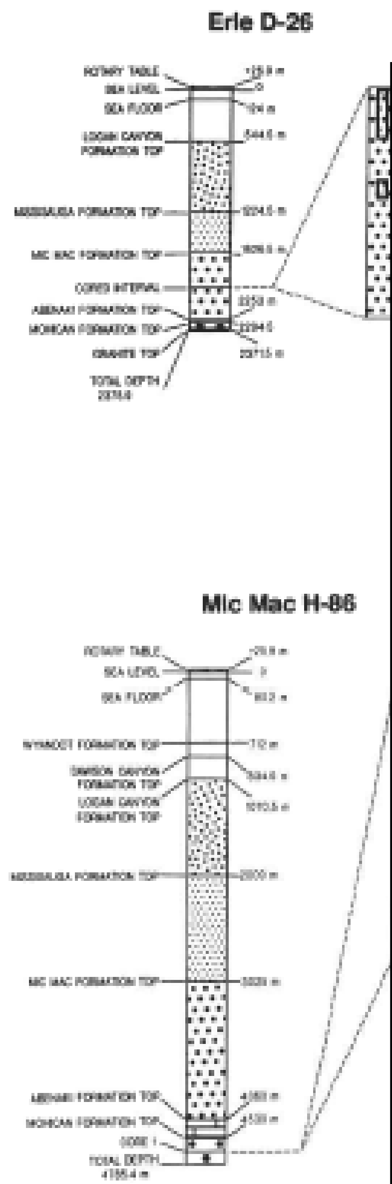
Thermal Inversion
Illite
Smectite clay
OIL WINDOW
Uncertainty
Temperature, C
Deposition of sand in basin
Uncertainty
Present day T
In well
200
180
160
140
120
100
80
60
40
20
0
100
50
0
Million years before present



e.g.
Thebaud I-94
well at
3.7 km



200
180
160
140
120
100
80
60
40
20
0
Temperature, C
GAS WINDOW
OIL WINDOW
Deposition of sand in basin
Present day T
In well
Illite
Smect.
100
50
0
Million years before present



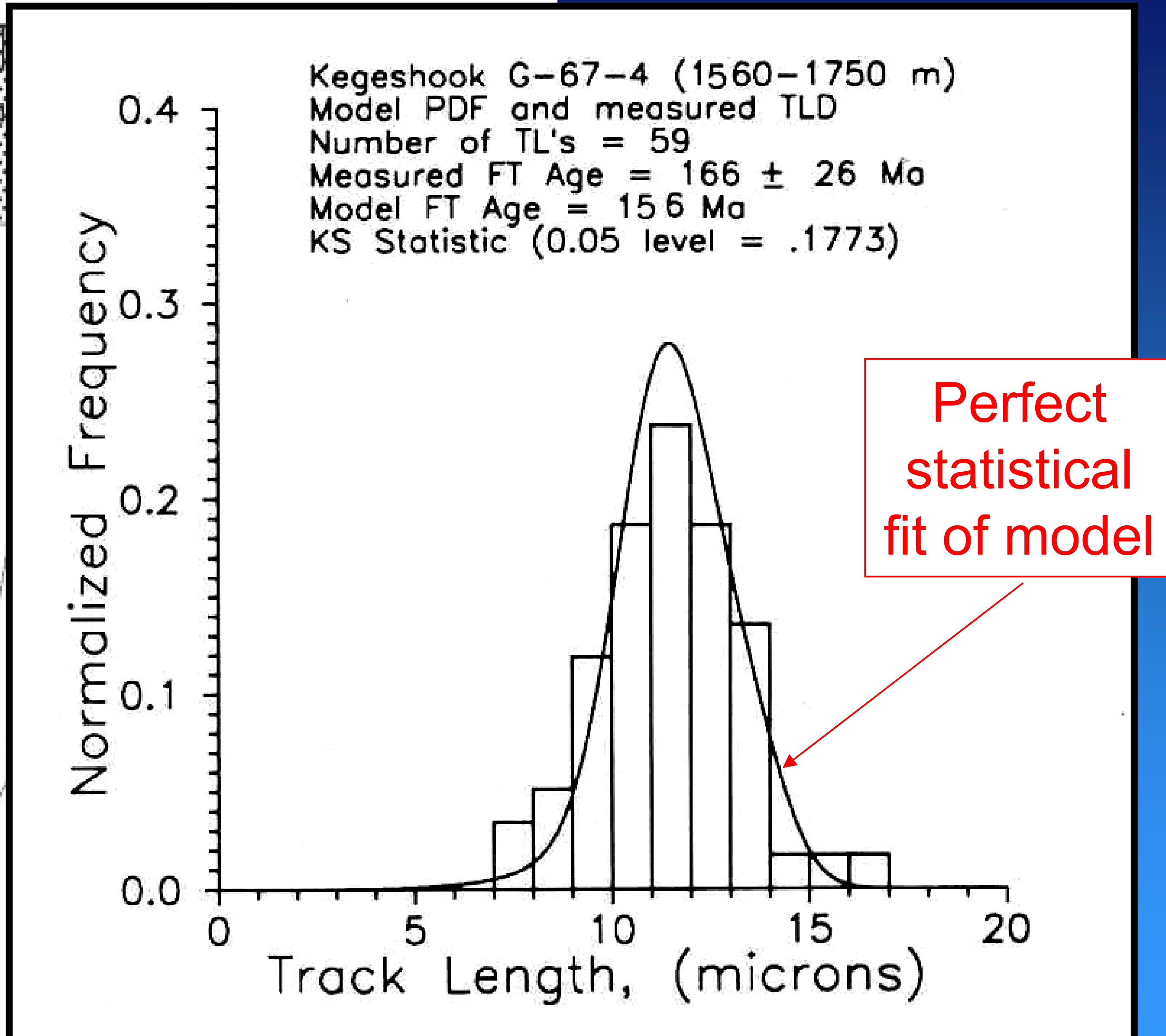
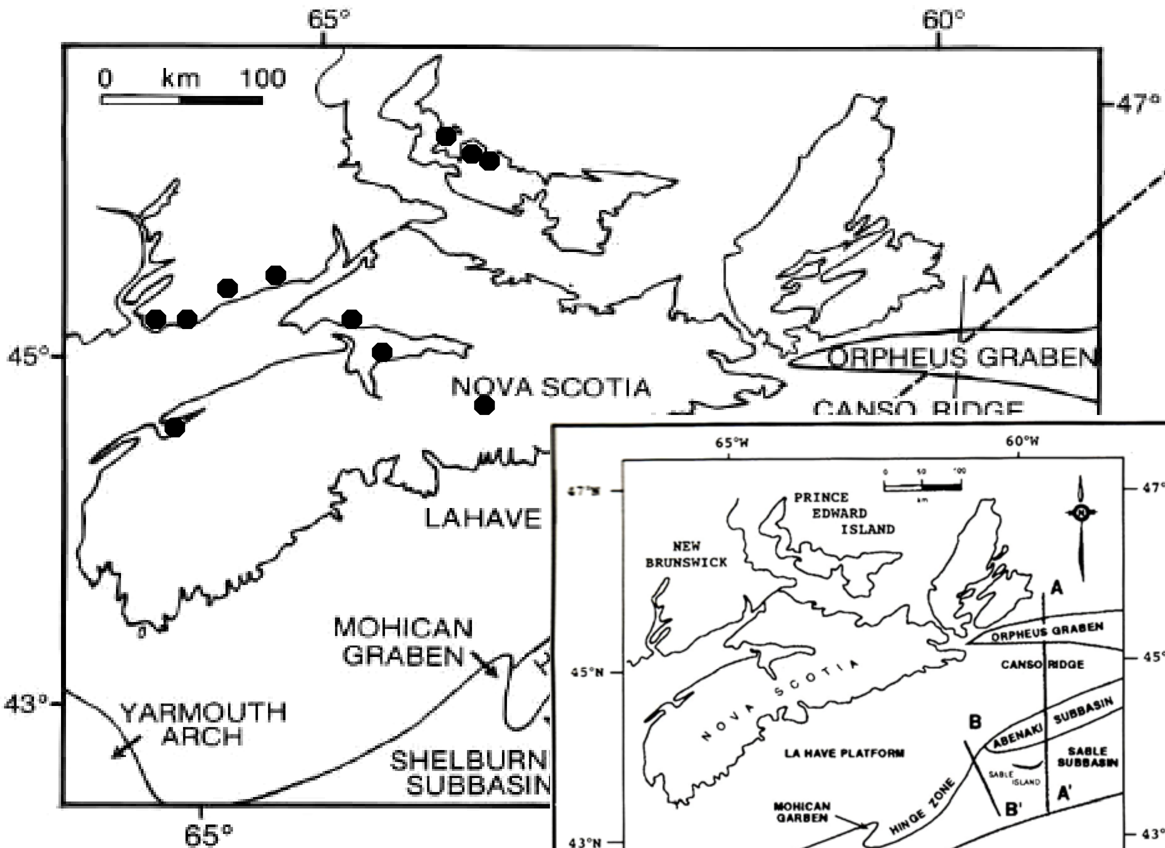
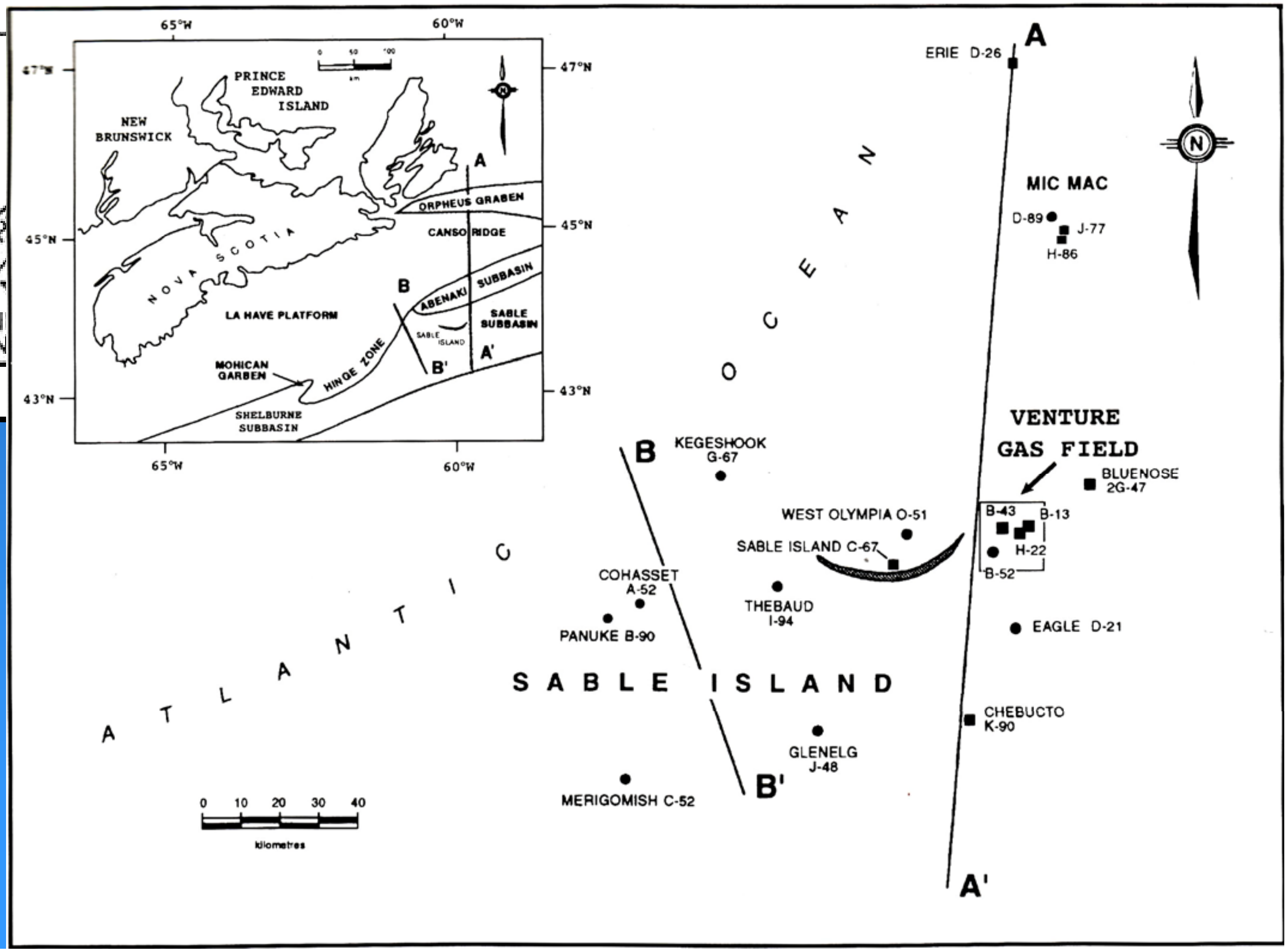


FIG. 3. Stratigraphy of the nine wells sampled for this study. Locations of samples are shown in the expanded views of the cored sandstone intervals. Depths to formation tops are drilling depths (i.e., below rotary table). Stratigraphic picks are from the 1986 "Offshore schedule of wells."



Grist et al. 1992

Li et al. 1995



Grist & Zentilli 2003

Onshore Nova Scotia also experienced post mid-Cretaceous heating and Oligocene (?) cooling

The Future
Paleotemperature Time Slices

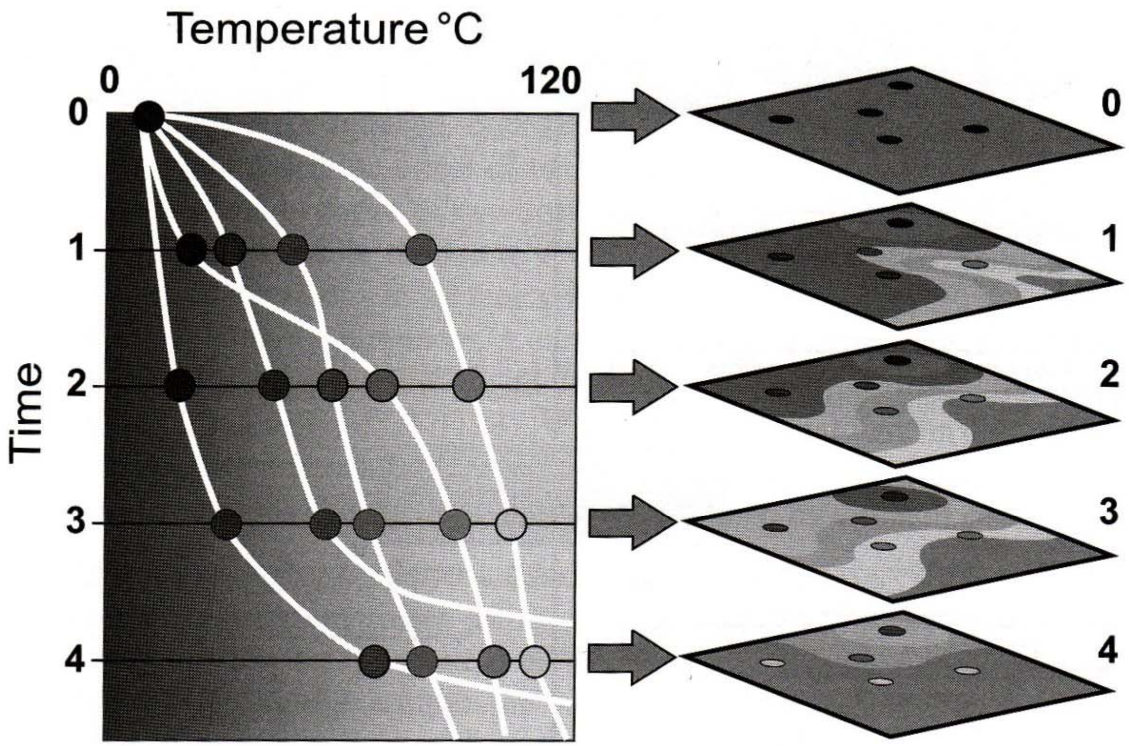


Figure 4. Derivation of paleotemperature images. Following the sequential thermal history modeling of samples within a regional subset, a series of time-temperature curves (white lines, left panel) are derived. Then for different nominal time slices (1-4) paleotemperatures for different samples (filled circles) can be spatially interpolated on a regional map and compiled as a series of time-slice image stacks. Such stacks can then be visualized as a time sequence (and also as a digital movie) showing how temperature of present day surface rocks has varied through time. Such stacks can also be extended to image denudation and paleotopography (see Fig. 3 and text).

Kohn et al. 2005

Summary

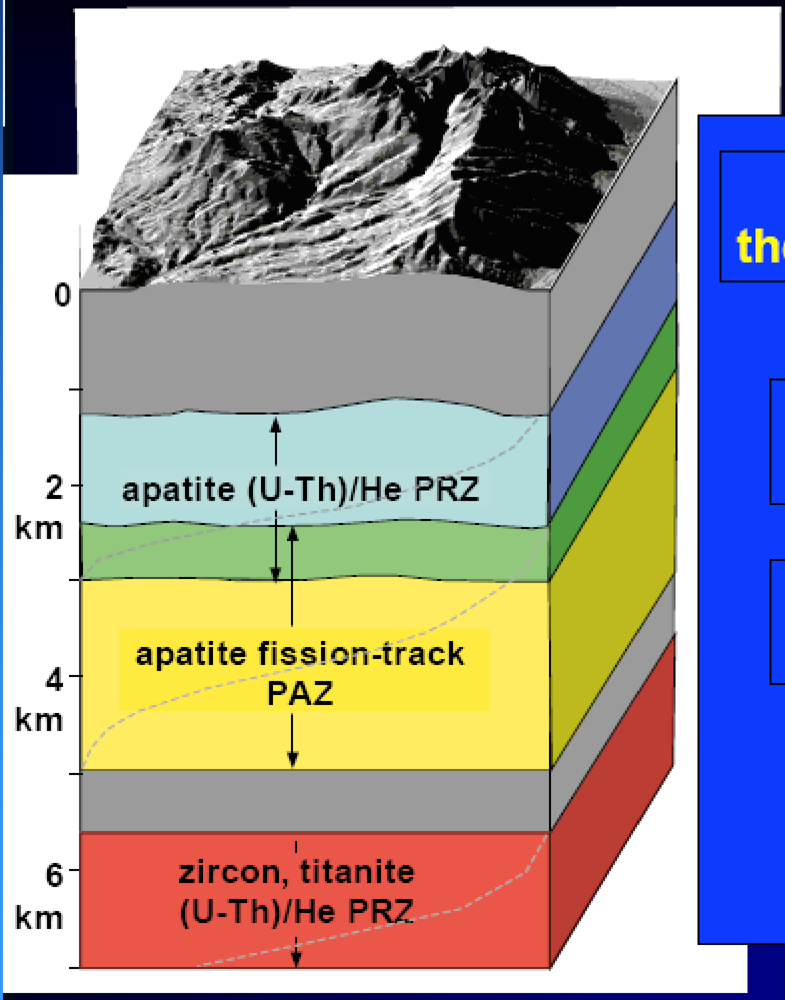
- **Apatite Fission Track Dating**
  - Dates last time the rock cooled through ~100°C
- **Fission Track Length Inverse Modelling**
  - Time-temperature histories 125 – 65°C

- Dating of fault movement
- Thermal effects of salt
- Dating of basin inversion

(Uranium-Thorium-Samarium)/He

- Also available in Canada only at Dalhousie University
- Uses mass spectrometer
- Apatite most suitable (t ~ 70^{o}C)
- Grain size influence
- C

Combined methods best approach



Low- and mid-T thermochronometers

apatite (U-Th)/He
T_c ~ 70°C

apatite fission-track
T_c ~ 110°C

Zircon (U-Th)/He
T_c ~ 180-200°C

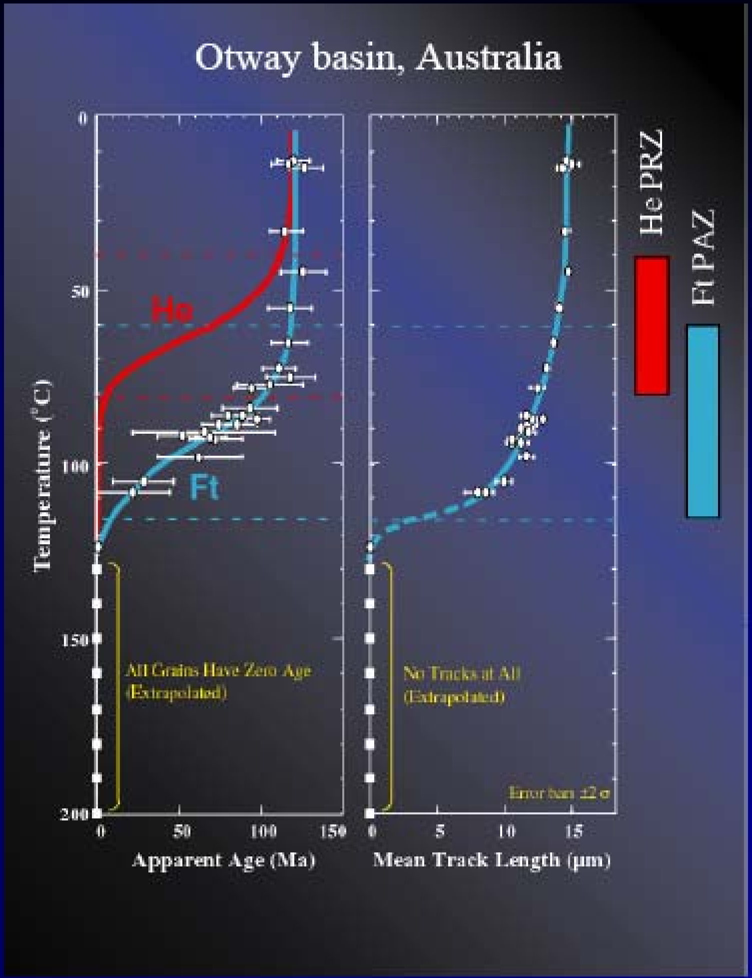
Stockli (2005) GAC Short Course

AFT versus (U-Th)/He

Can we extrapolate the experimental ^4He diffusion data to geologic time scales with confidence?

Apatite fission track: PAZ: 60-110°C

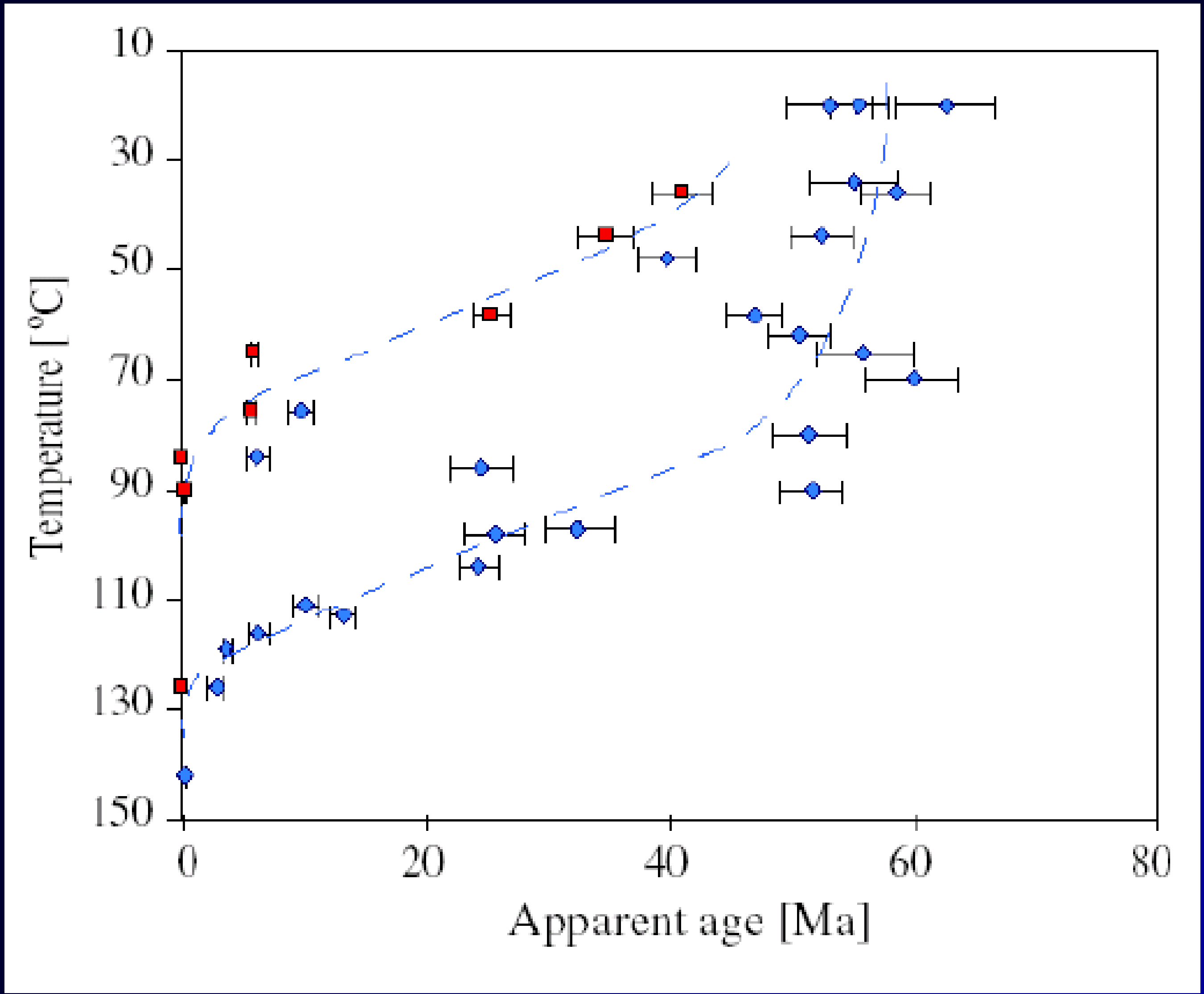
HePRZ: 40-80°C?



Recent advances and future of (U-Th)/He thermochronology:

- Laser He extraction and single crystal dating
- Extraction of thermal history data from single samples using multi-grain-size approach
- Integration and intercalibration with $^{40}Ar/^{39}Ar$ K-feldspar MDD modeling
- Expansion of technique to other U- and Th-bearing phases
- $^{4}He/^{3}He$ thermochronometry
- Integration with other techniques, e.g., cosmogenic nuclide dating or fluid inclusion studies

Cajon Pass drill hole data: apatite fission track (B. Kohn, unpubl.) and apatite (U-Th)/He (Wolf, 1998).



Cajon Pass drill hole, California

Wolf (1998)

Summary

- **Apatite Fission Track Dating**
  - Dates last time the rock cooled through ~100^{o}C
- **Fission Track Length Inverse Modelling**
  - Time-temperature histories 125 – 65^{o}C
- **(Uranium-Thorium-Samarium)/He** provides independent confirmation of AFT models; best used in combination

- Dating of fault movement
- Thermal effects of salt
- Dating of basin inversion

Suggested Comprehensive Reference

P.W. Reiners & T.A.Ehlers (Editors) Low-Temperature Thermochronology: Techniques, Interpretations, and Applications. Mineralogical Society of America. Reviews in Mineralogy & Geochemistry Volume 58 (2005) 622p. Available at www.minsocam.org