Episodic Regional Burial and Subsequent Exhumation Exert a Major Influence on Hydrocarbon Prospectivity*

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Abstract

In basins with complex histories, conventional basin modelling invariably combines burial histories based on the preserved stratigraphic section with variable heat flow to match calibration data (usually vitrinite reflectance). However, numerous studies involving application of low temperature thermochronology (principally apatite fission track analysis) combined with VR have shown that thermal history is often controlled not by variation in heat flow but by deeper burial and subsequent exhumation, in which km-scale section is deposited and subsequently removed typically within 30 Myr or less. These episodes are not restricted to basins, but also affect adjacent basement regions across areas of several 10^4 km^2. The origin of such events has long been debated. Due to the regional extent, the resulting unconformities are often very low angle, and the corresponding time intervals are often erroneously interpreted as periods of stability and non-deposition. The notion of deeper burial and subsequent exhumation during these intervals is sometimes questioned because of the lack of an accepted mechanism. Nevertheless, a large body of data points to the reality of these events. It has also become clear that these exhumation episodes are broadly synchronous over vast regions. Three phases of Cenozoic exhumation are recorded in areas from Alaska to Greenland, Norway and Svalbard, while exhumation episodes ranging in time from Carboniferous to Cenozoic appear to be broadly synchronous in Brazil, South Africa, and Australia. The lack of attention to missing section contrasts starkly with the effort devoted to the preserved section. Yet in many basins hydrocarbon prospectivity is controlled by deposition and removal of the missing section rather than elevated heat flow. Deeper burial leads to enhanced maturity levels while mistaking the effects of deeper burial for elevated heat flow can lead to incorrect discounting of deep source potential. Exhumation can lead to remigration and loss of charge due to seal breach and phase change. Understanding the controlling processes is essential in order to accurately define the variation of maturity in time and space so as to identify more prospective regions, and geodynamic models are required that can provide a mechanism. Meanwhile, basin modelling studies should focus more on deposition and removal of km-scale thicknesses of section instead of elevated heat flow.

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Waples, D.W., H. Kamata, and M. Suizu, 1992, The Art of Maturity Modeling. Part 1: Finding a Satisfactory Geologic Model: AAPG Bulletin, v. 76/1, p. 31-46.

Episodic regional burial and subsequent exhumation exert a major influence on hydrocarbon prospectivity

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The art of basin modelling: Waples et al 1992

The American Association of Petroleum Geologists Bulletin
V. 76, No. 1 (January 1992), P. 31-46, 9 Figs., 2 Tables

The Art of Maturity Modeling. Part 1: Finding a Satisfactory Geologic Model[1]

Douglas W. Waples, Hiromi Kamata, and Masahiro Suizu[2]

ABSTRACT

An example of one-dimensional maturity modeling of the MITI Rumoi well, a stratigraphic test drilled in a frontier area of Japan, is worked out in detail to illustrate how maturity modeling should be carried out.

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The logistics of maturity modeling are discussed in detail elsewhere (Waples, in press). Briefly summarized, we first make a best estimate of the burial, erosional, and thermal history of the area based on all available geological and geophysical data. We then check the correctness of some aspects of this model (particularly present heat flow and thermal conductivities of rocks) by comparing measured present-day formation temperatures with predictions made using the model. Once a plausible set of input values for these parameters has been established, paleoheat flow and amounts of erosional removal are deduced by comparing predicted and measured values for thermal indicators. When a plausible burial, erosional, and thermal history has been established that is consistent with our geologic concepts and measured data, we can then model the process of hydrocarbon generation.

Things to deduce:

1: paleo-heat flow

2: erosional removal

Basic premise

In our experience, basin modellers (and others) are happy to vary paleo-heat flow to match calibration data (usually vitrinite reflectance), but are much more hesitant when it comes to incorporating erosional removal (i.e. deeper burial and subsequent exhumation).

However, in routine application of AFTA (apatite fission track analysis) combined with VR in many sedimentary basins around the world, we have found that thermal history is often controlled not by variation in heat flow but by deeper burial and subsequent exhumation.

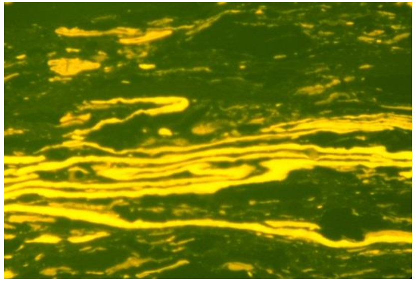
These events involve deposition and subsequently removal of km-scale section, typically within intervals of a few 10s of Myr or less.

These episodes are not restricted to basins, but also affect adjacent basement regions, and extend across areas of several 10^4 km^2.

The cause of these episodes is unknown, but must act on a plate scale.

Measuring missing section

The key to accurate modelling of maturation histories lies not only in describing the rocks that are present but also in understanding the rocks that were once present but have now been removed by erosion.



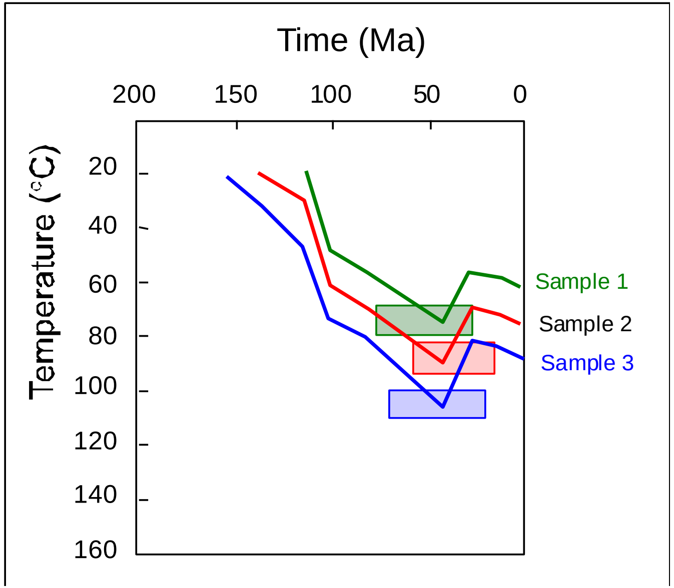
For this purpose, our principal tools are AFTA (Apatite Fission Track Analysis, above) and vitrinite reflectance (right).

Thermal history reconstruction - 1

THR relies on application of AFTA (Apatite Fission Track Analysis®) and Vitrinite reflectance (VR) to:

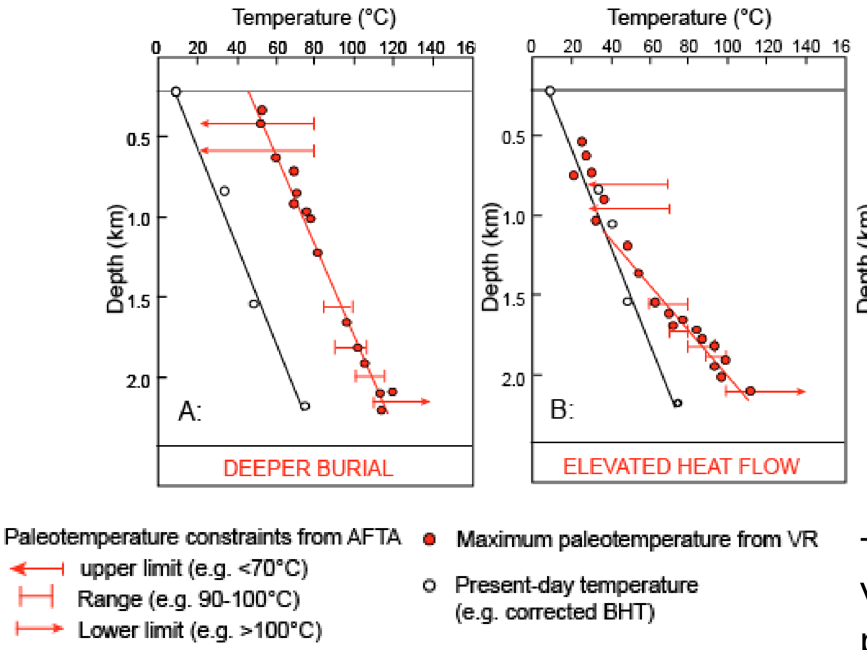
Identify the timing of dominant episodes of heating and cooling that have affected a sedimentary section:

Quantify the variation of paleotemperatures through the section:



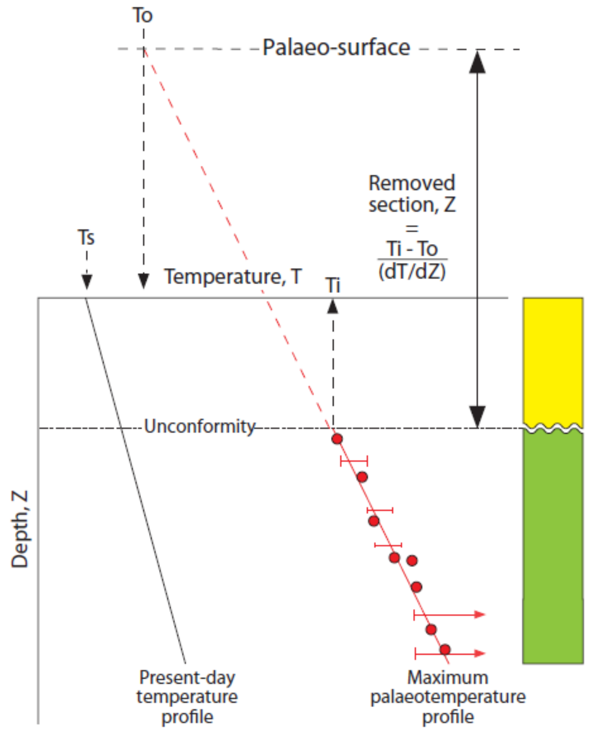
Thermal history reconstruction - 2

And to *characterise* mechanisms of heating and cooling

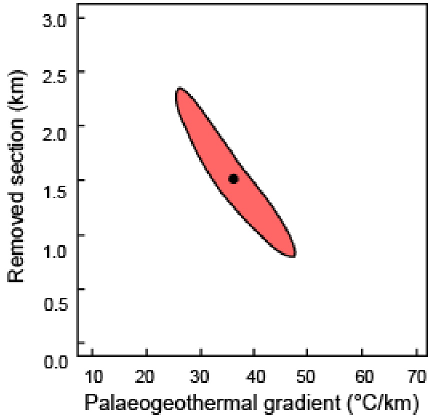


The variation of paleotemperatures from AFTA and VR with depth provides direct insight into the processes responsible for heating and cooling.

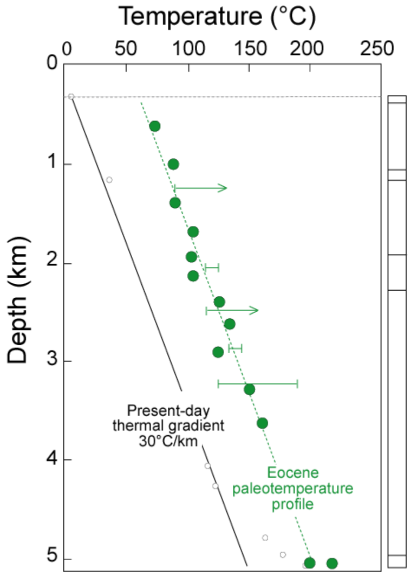
Paleogeothermal gradients and missing section

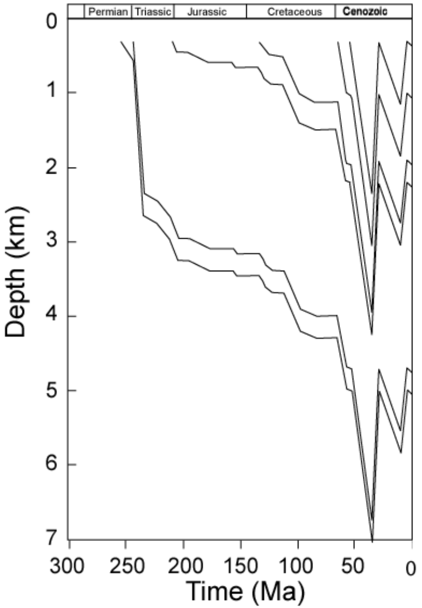


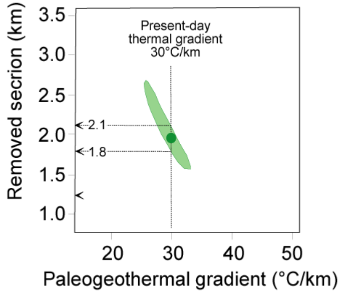
Ts	Present-day surface temperature
To	Palaeo-surface temperature
Ti	Palaeotemperature intercept at unconformity
(dT/dZ)	Palaeogeothermal gradient
(red bar)	Palaeotemperature from AFTA
(red dot)	Palaeotemperature from VR

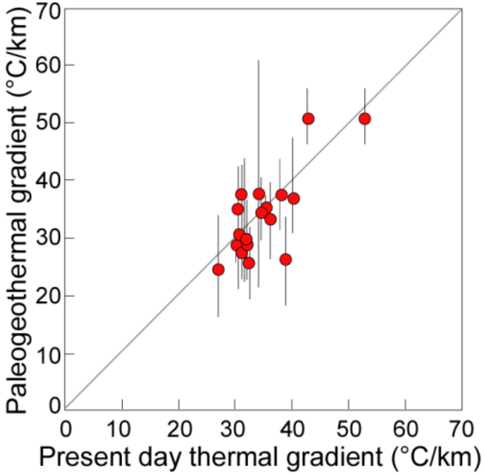


Barents Sea - 1





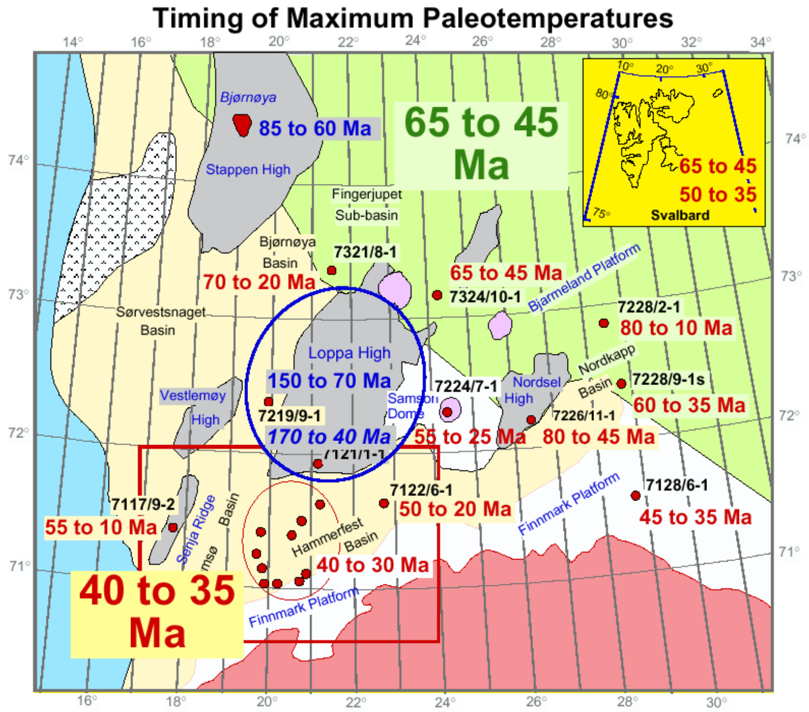




AFTA and VR data show that ~2 km of additional section was deposited prior to the onset of exhumation in the interval 40 to 20 Ma.

Results show no evidence of elevated heat flow. Cooling was due solely to exhumation.

Barents Sea - 2



Results from other wells around the Barents Sea consistently define three episodes of exhumation, beginning in these intervals:

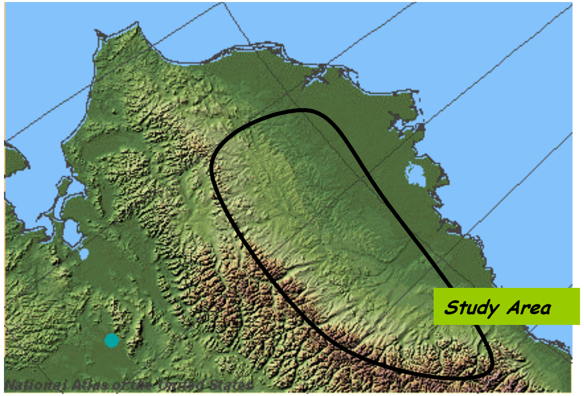
65 to 45 Ma

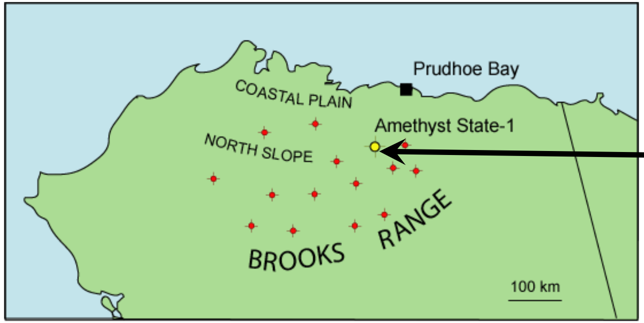
40 to 35 Ma

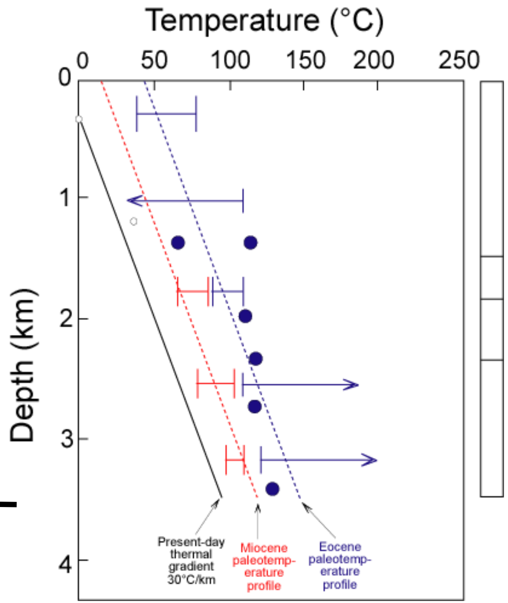
10 to 0 Ma

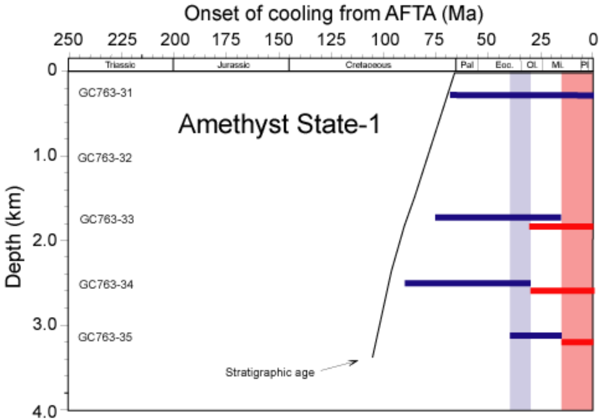
The earliest episode is seen only in the northeast, where no Paleogene sediments are preserved. The two more recent episodes affected the whole region.

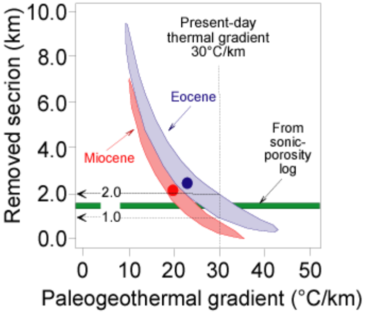
Alaska North Slope - 1



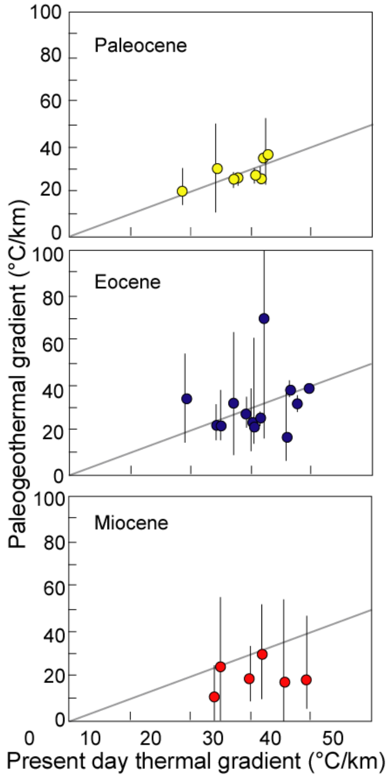




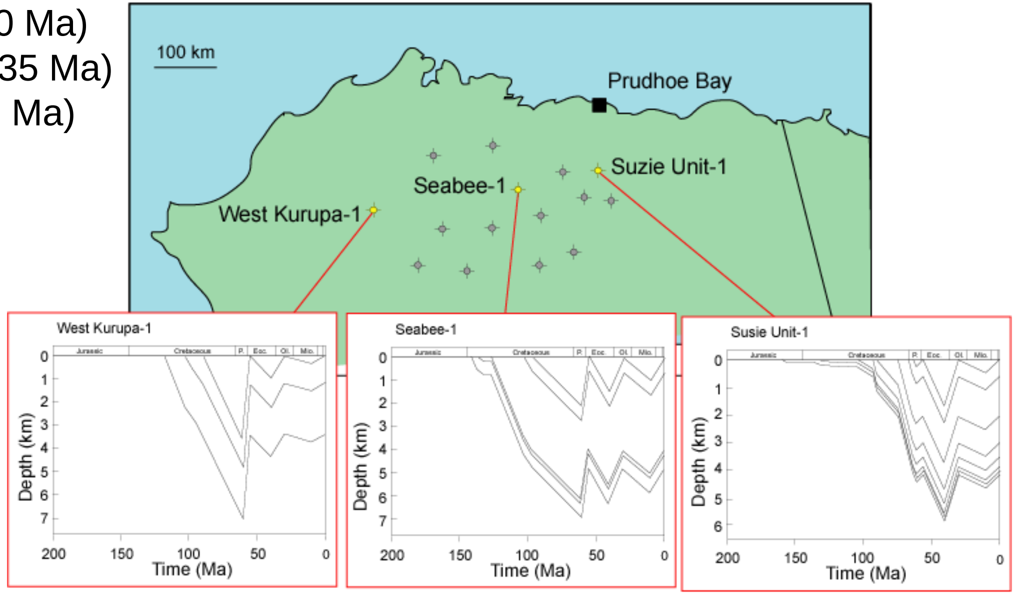




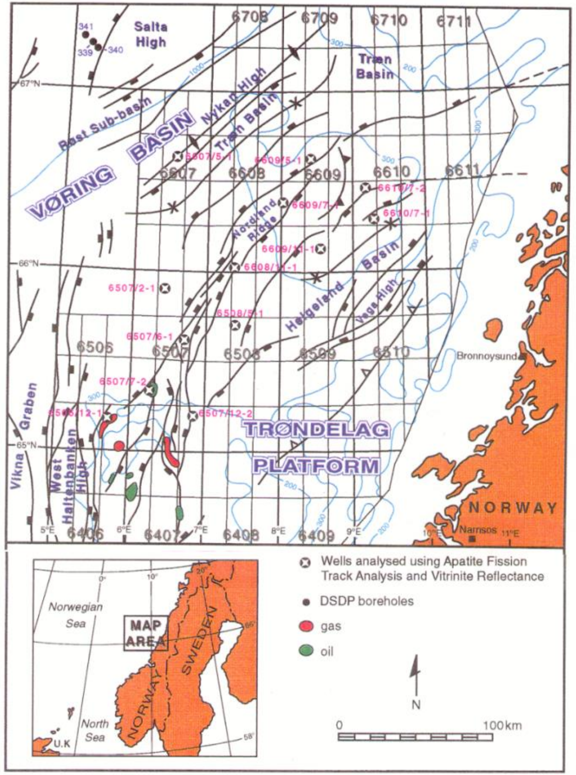
Alaska North Slope - 2



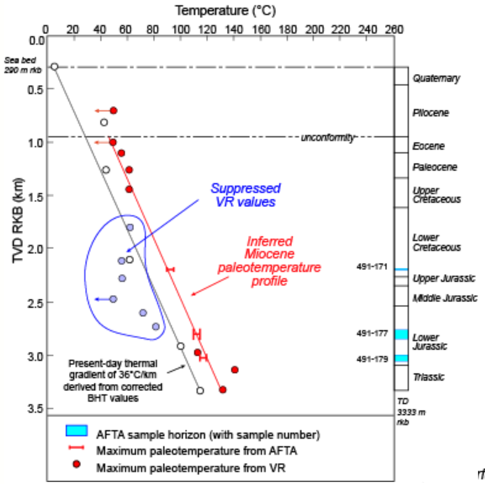
AFTA reveals repeated cycles of burial and exhumation, beginning in these intervals:
Early Tertiary (60 - 50 Ma)
Middle Tertiary (40 - 35 Ma)
Late Tertiary (15 - 10 Ma)



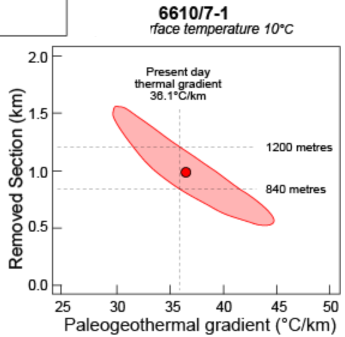
Mid-Norway - 1



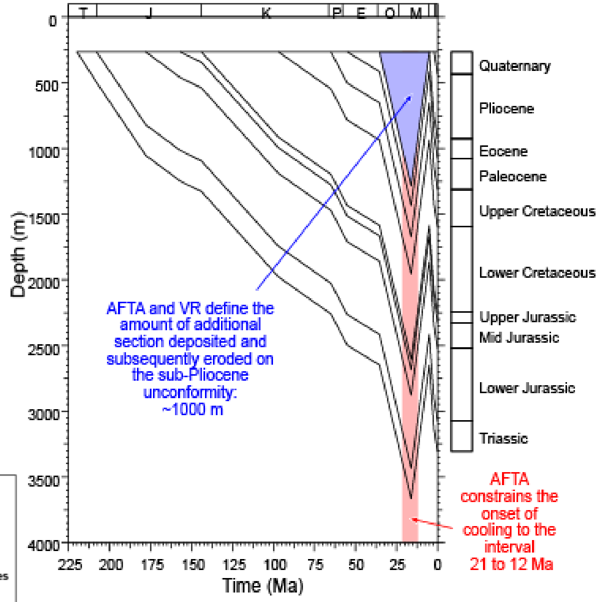
Salta High
Træn Basin
Vøring Basin
Nykan High
Træn Basin
Nordland Ridge
Helgeland Basin
Vega High
Trøndelag Platform
Vikna
Halten Graben
West Haltenbanken High
Bronnoysund
Namsos
NORWAY
6708
6709
6710
6711
6607
6608
6609
6610
6611
6506
6507
6508
6509
6510
6406
6407
6408
6409
Norwegian Sea
MAP AREA
SWEDEN
NORWAY
North Sea
U.K
Wells analysed using Apatite Fission Track Analysis and Vitrinite Reflectance
DSDP boreholes
gas
oil
N
0
100km



Temperature (°C)
0 20 40 60 80 100 120 140 160 180 200 220 240 260
TVD RKB (km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Sea bed 290 m rkb
unconformity
Suppressed VR values
Inferred Miocene paleotemperature profile
Present-day thermal gradient of 36°C/km derived from corrected BHT values
Quaternary
Pliocene
Eocene
Paleocene
Upper Cretaceous
Lower Cretaceous
Upper Jurassic
Middle Jurassic
Lower Jurassic
Triassic
491-171
491-177
491-179
TD 3333 m rkb
AFTA sample horizon (with sample number)
Maximum paleotemperature from AFTA
Maximum paleotemperature from VR



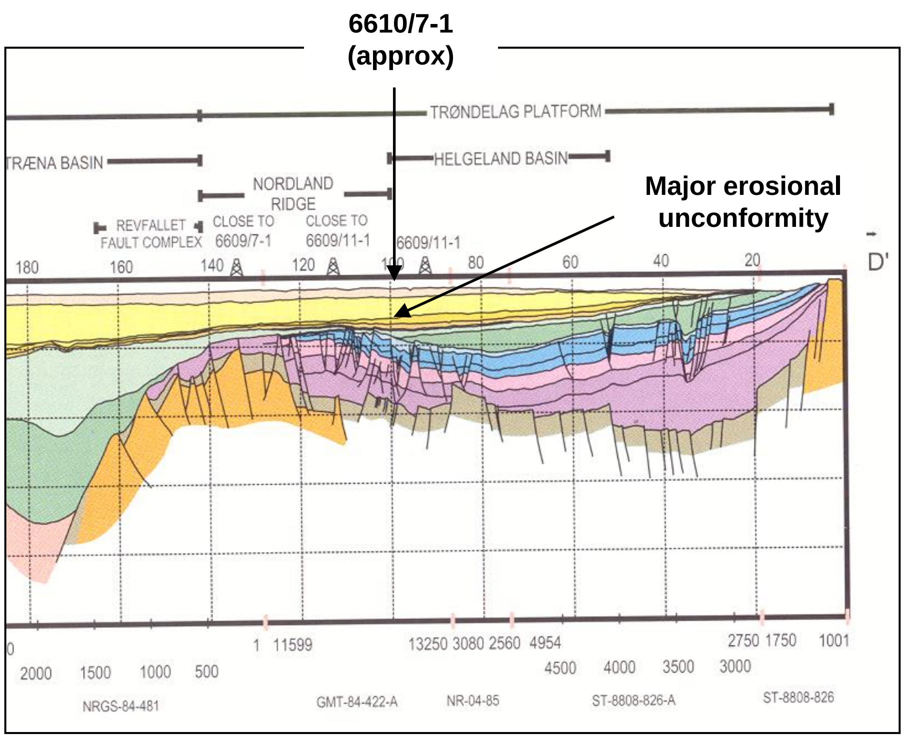
6610/7-1
rface temperature 10°C
Removed Section (km)
2.0
1.5
1.0
0.5
0.0
Present day thermal gradient 36.1°C/km
1200 metres
840 metres
25 30 35 40 45 50
Paleogeothermal gradient (°C/km)



T J K P E O M
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
225 200 175 150 125 100 75 50 25 0
Time (Ma)
Quaternary
Pliocene
Eocene
Paleocene
Upper Cretaceous
Lower Cretaceous
Upper Jurassic
Mid Jurassic
Lower Jurassic
Triassic
AFTA and VR define the amount of additional section deposited and subsequently eroded on the sub-Pliocene unconformity: ~1000 m
AFTA constrains the onset of cooling to the interval 21 to 12 Ma

Mid-Norway - 2

The episode of deeper burial and exhumation identified from AFTA corresponds to an interval where for which no section is preserved, previously thought to be a period of non-deposition.



From: Brekke 2000, Geol Soc Spec Pub 167, pp327-378

Controversy over missing section

The idea of missing section – significant amounts (km-scale) of section that were deposited and subsequently eroded away – has been the subject of controversy in many areas, e.g.

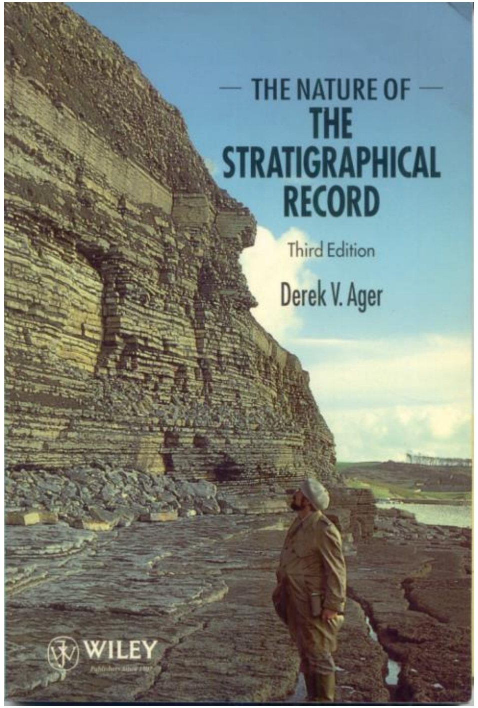
Sydney Basin

UK East Midlands Shelf

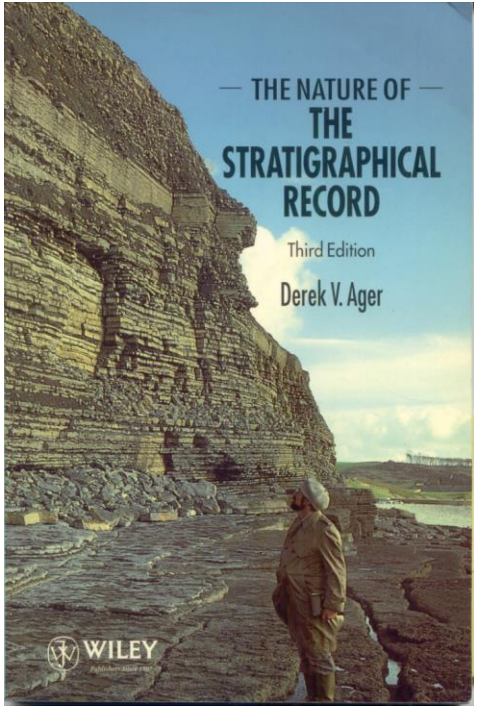
Appalachian Basin

But the concept is actually quite consistent with the imperfect nature of the stratigraphic record.

The nature of the stratigraphic record



What happened during the gaps?



Was it this?

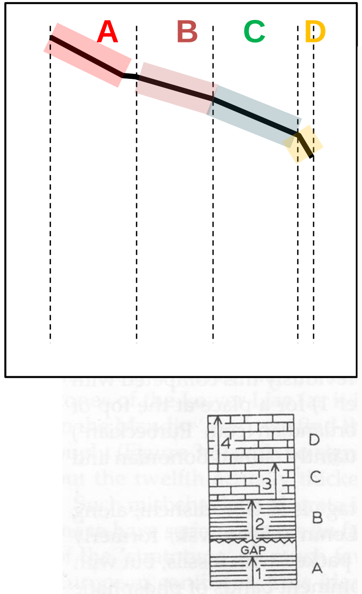
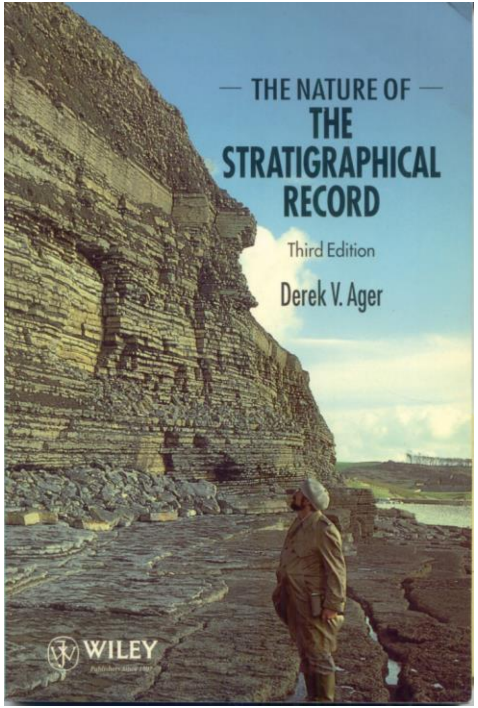
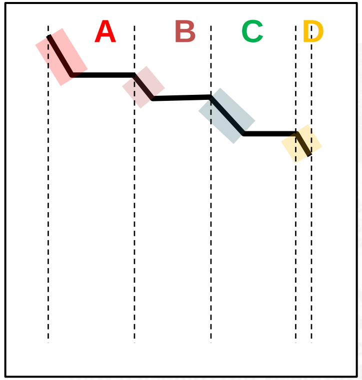


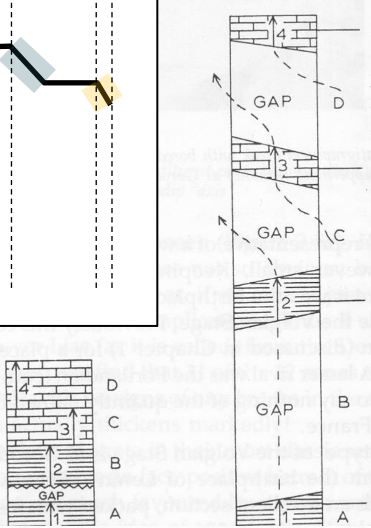
Figure 3.8 Comparison of the conventional picture of a particular part of the stratigraphical record (left) with what is probably the true picture (right); see text for explanation

What happened during the gaps?



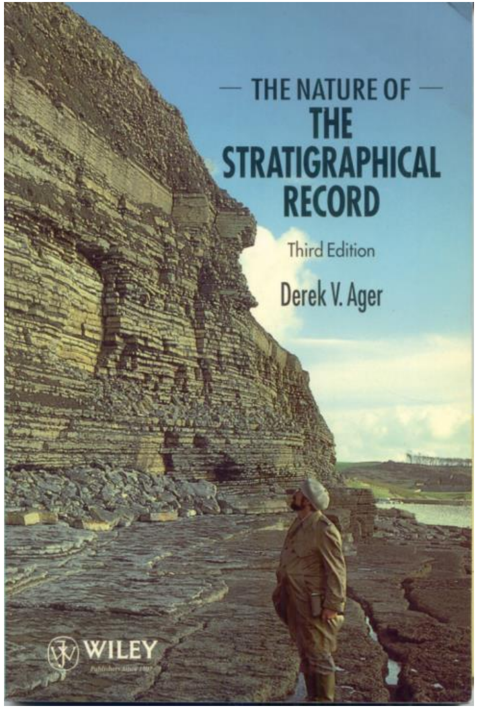
Or this?





So we may come to the third proposition of this book: *the sedimentary pile at any one place on the earth's surface is nothing more than a tiny and fragmentary record of vast periods of earth history.* This may be called the 'Phenomenon of the Gap Being More Important than the Record'.

What really happened during the gaps?



We often see this!

AFTA and VR often reveal major periods of heating and cooling, representing deposition and removal of km-scale thicknesses, during time intervals represented by gaps in the preserved section.

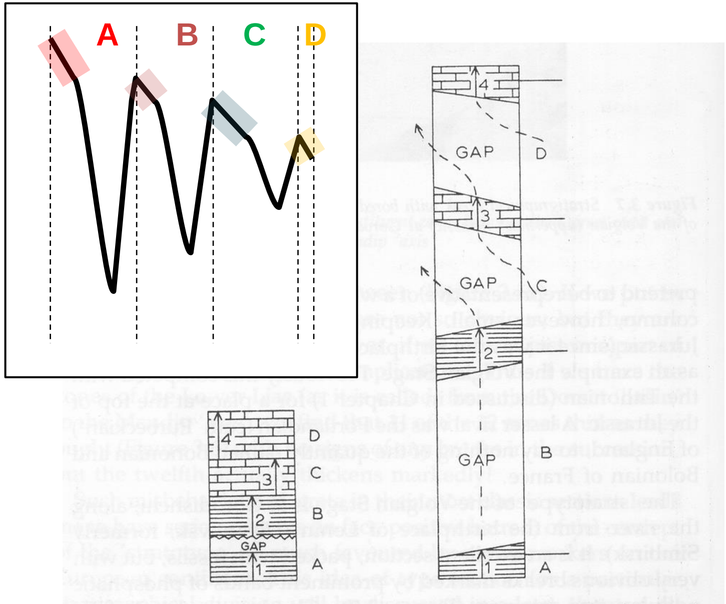


Figure 3.8 Comparison of the conventional picture of a particular part of the strati-graphical record (left) with what is probably the true picture (right); see text for explanation

Stratigraphy as a set of frozen accidents

Updating uniformitarianism: stratigraphy as just a set of 'frozen accidents'

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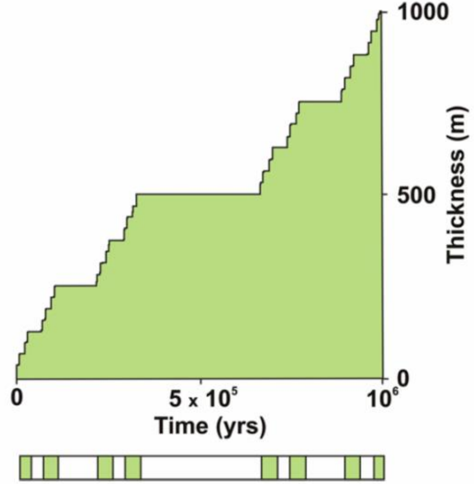
Abstract: It has long been understood that the stratigraphic record is fragmentary.



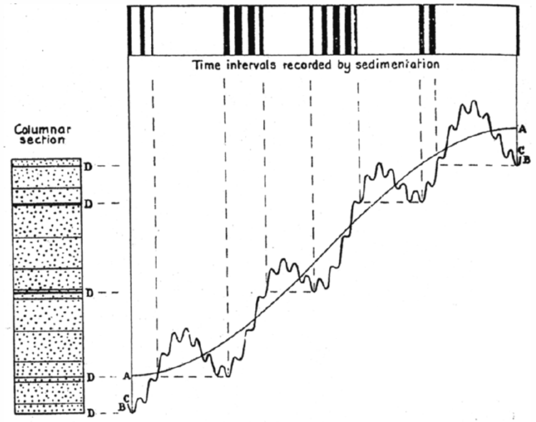


FIGURE 5.—*Sedimentary Record made by harmonic Oscillations in Baselevel*

A-A. Primary curve of rising baselevel.
B-B. Diastrophic oscillations, giving disconformities D-D.
C-C. Minor oscillations, exaggerated and simplified, due largely to climatic rhythms
Equation of curve C-C: $y = \sin x - .25 \cos 8x - .05 \cos 64x$.

Fig. 1. Explanation of how oscillatory variations in base level control the timing of deposition (from Barrell 1917). Sedimentation can only occur when base level is actively rising. These short intervals are indicated by the black bars in the top diagram. The resulting stratigraphic column, shown at the left, is full of disconformities, but appears to be the result of continuous sedimentation.

From: SMITH, D. G., BAILEY, R. J., BURGESS, P. M. & FRASER, A. J. (eds) 2015. *Strata and Time: Probing the Gaps in Our Understanding*. Geological Society, London, Special Publications, **404**, 11–36.
First published online April 11, 2014, http://dx.doi.org/10.1144/SP404.4

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Key aspects of burial/exhumation episodes - 1

Events in which 1 km or more of section is deposited and subsequently removed within a few 10s of Myr are fairly common.

These events affect regions of several 10^4 km^2.

The regional extent results in very low angle unconformities, often mistaken for periods of non-deposition

Key aspects of burial/exhumation episodes - 2

Events in different continents often appear to be broadly synchronous (e,g, Paleocene, end-Eocene and Miocene events in Alaska, UK and West Greenland; Late Cretaceous in Brasil, South Africa and eastern Australia)

Events also appear to correlate with plate boundary events (e,g, end-Eocene in North Atlantic).

The nature of the controlling processes is unknown but must act on a plate scale.

The punchline

In many areas these events exert a critical influence on hydrocarbon prospectivity.

Implications for hydrocarbon prospectivity

Failure to appreciate the extent of deeper burial can lead to underestimation of maturity levels.

Tendency to explain elevated VR data by elevated basal heat flow will lead to over-prediction of maturity levels at depth.

Failure to recognise exhumation results in lack of appreciation of the effects of phase transformations and breach of seals, leading to loss of charge.

Closing thought

A huge amount of time, effort and money goes into seismic acquisition, processing and interpretation, sequence stratigraphy, biostratigraphy etc to define the preserved section.

Compare that with the lack of attention given to worrying about what's missing. Yet what's missing can ultimately result in a dry hole!