Fossil Fuels (part 2)

Lecture 20
Fundamentals of Earth Resources

L. M. Cathles
2017

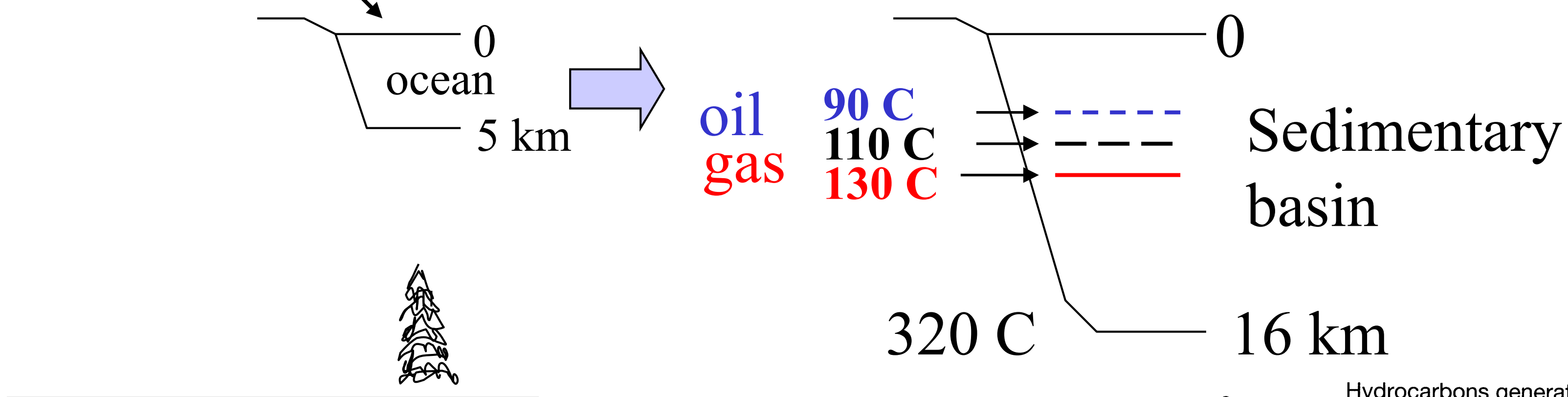
Outline

- Geology of Oil and Gas (Petroleum)
  - conventional
  - unconventional
- Resources
  - Conventional
  - Unconventional
- Duration of petroleum era?

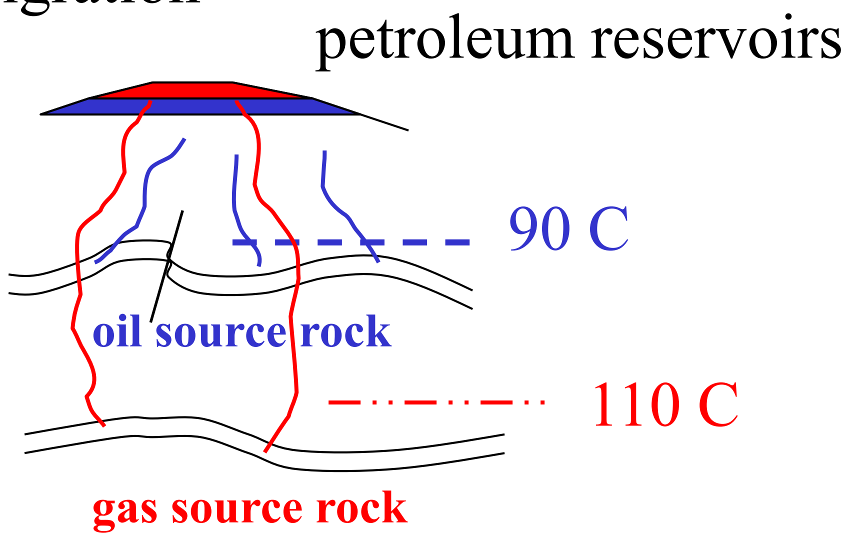
Sedimentary Basins: where products of erosion accumulate

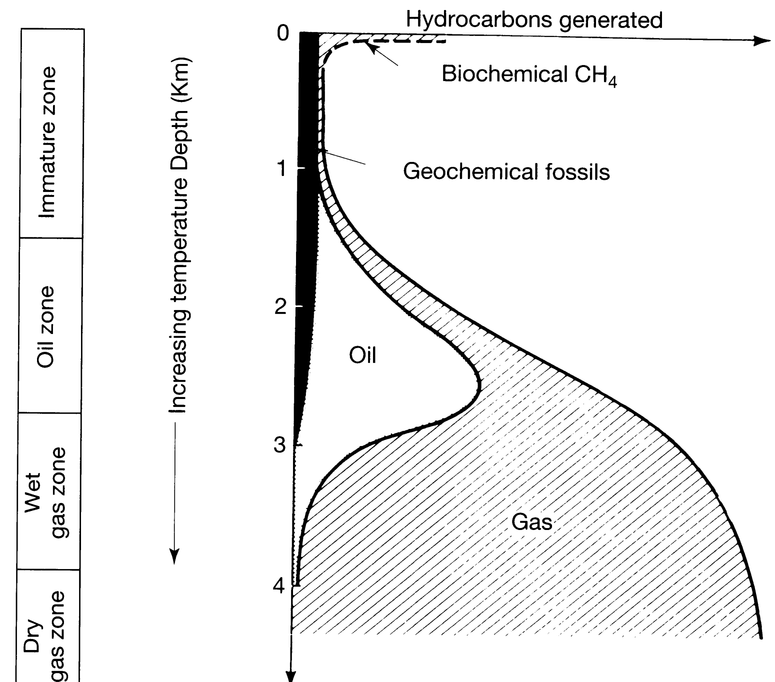
1. Sedimentation

2. Maturation

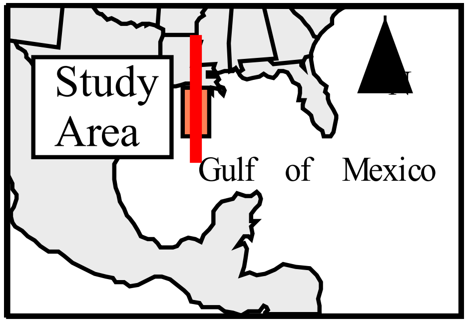


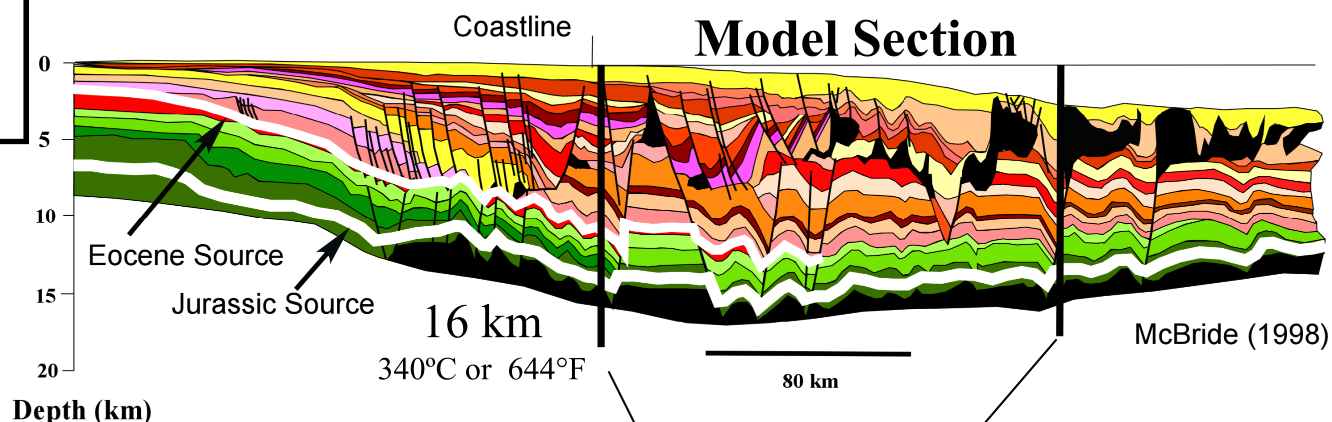
3. Migration

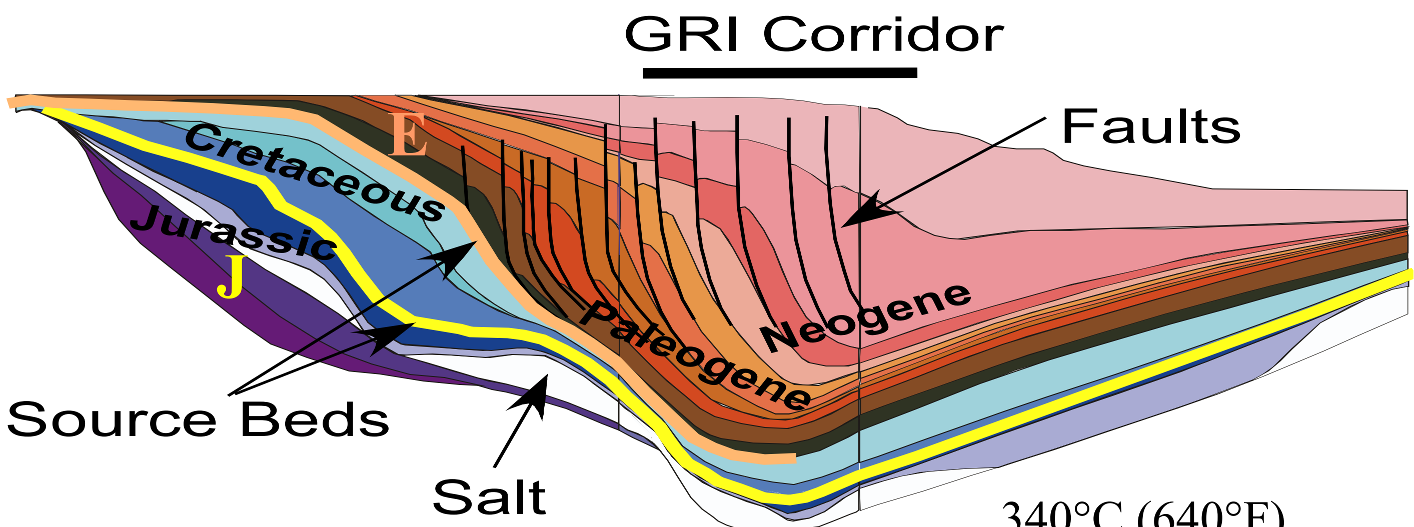




The GoM Example







Thin source beds ↓

140 my

53

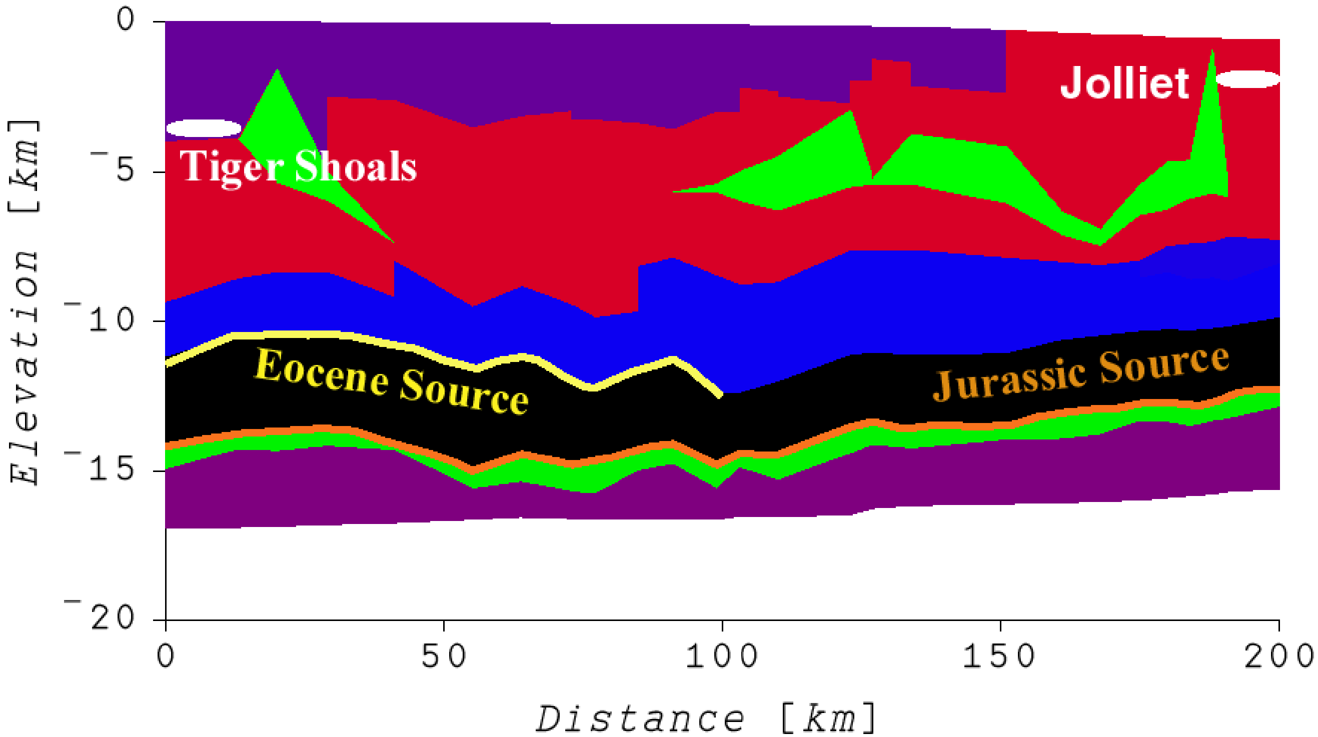
Jurassic TII: **0.1** x 125 x 202 km, 5Wt% TOC, HI=628 => **204 Bt HC**

Eocene TIII: **0.03** x 125 x 93 km, 4Wt% TOC, HI=204 => **6.9 Bt**

Infer salt movement from sedimentation ⇒

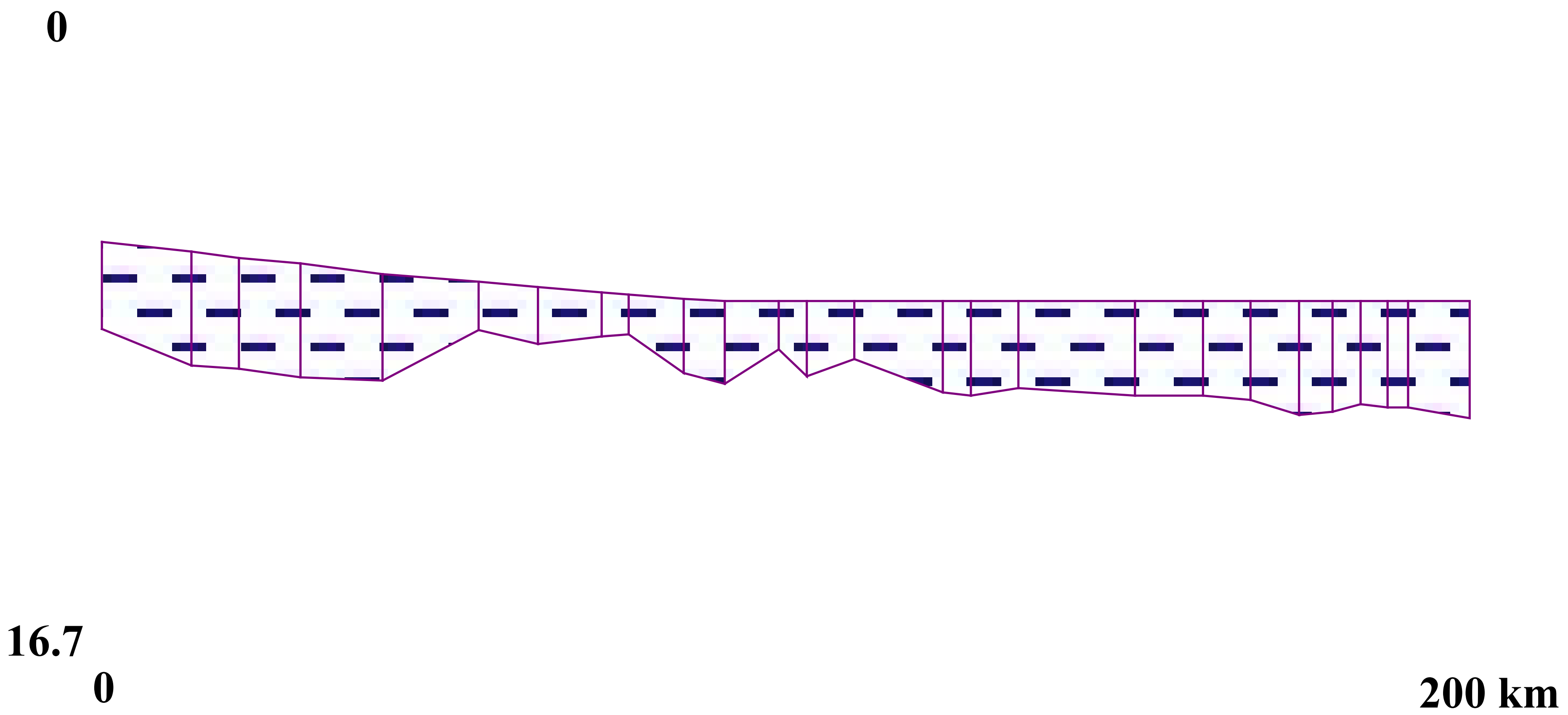
Cathles (2004)

Migration of HC from 2 Sources



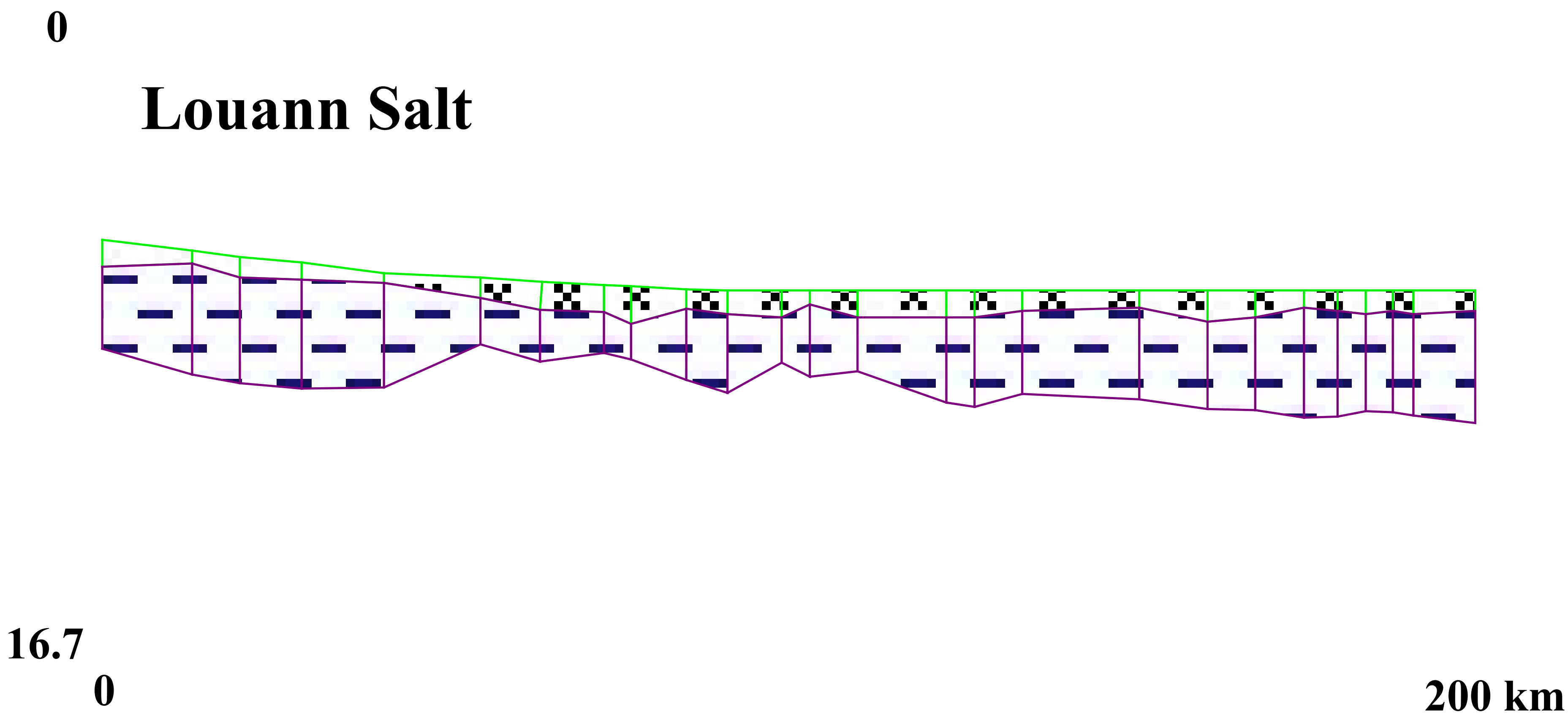
Cathles (2004)

149 Ma



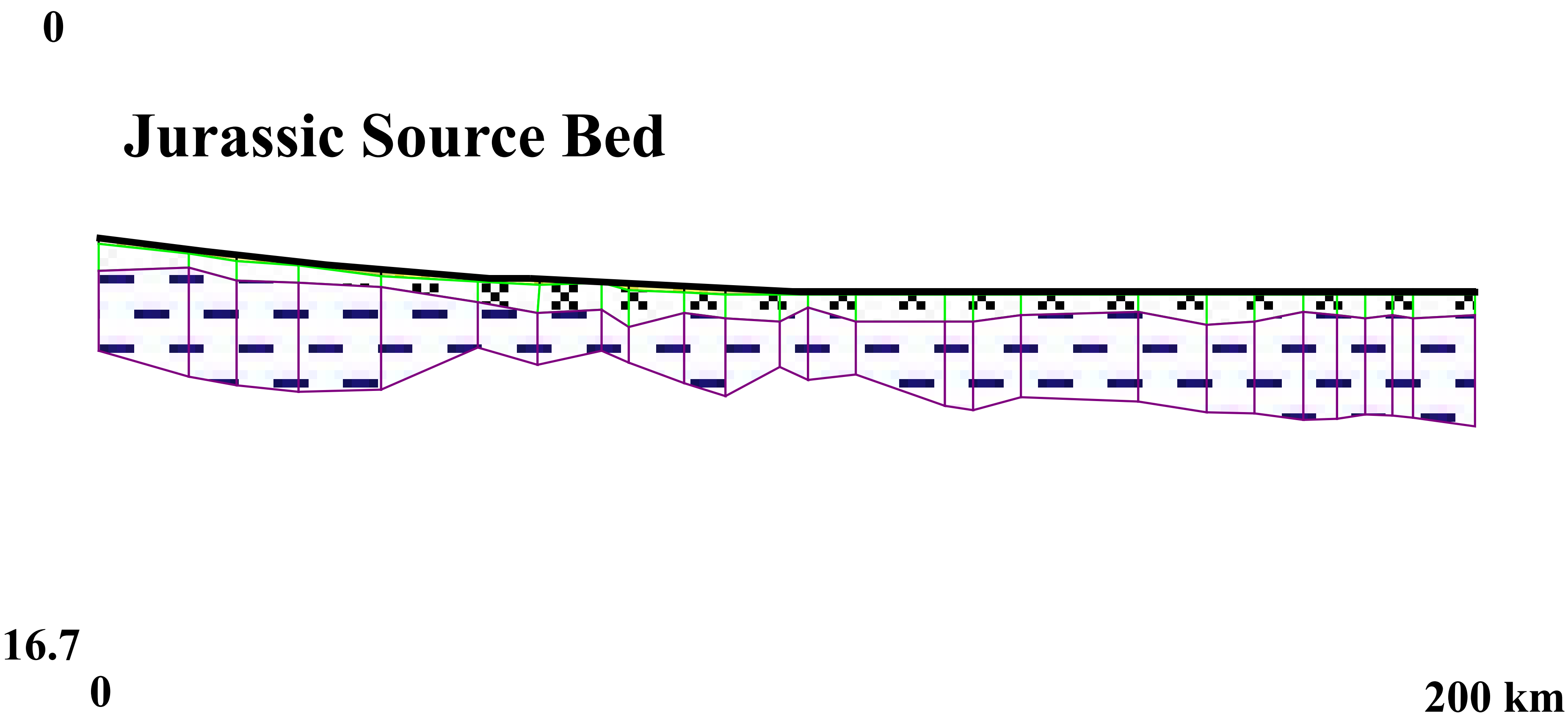
Cathles (2004)

144 Ma



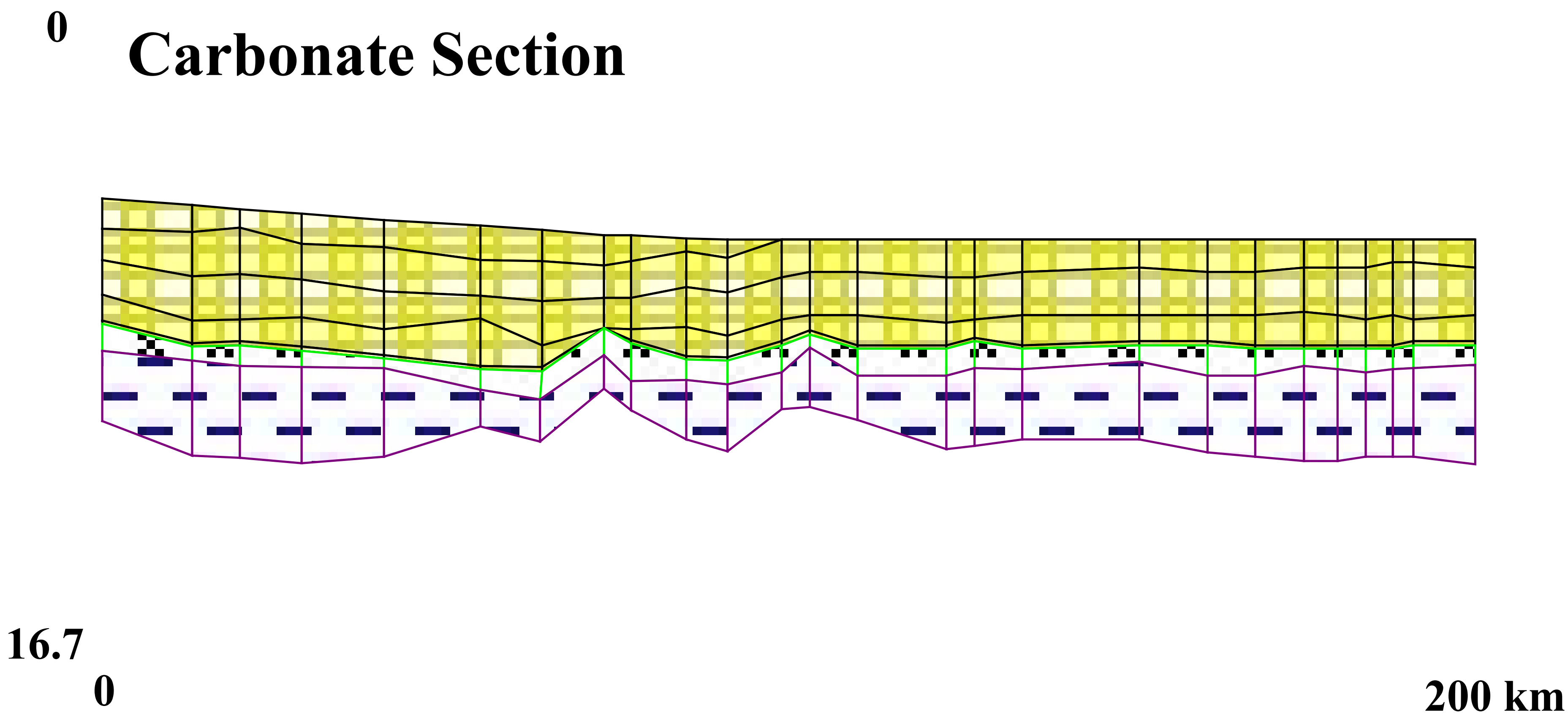
Cathles (2004)

138 Ma



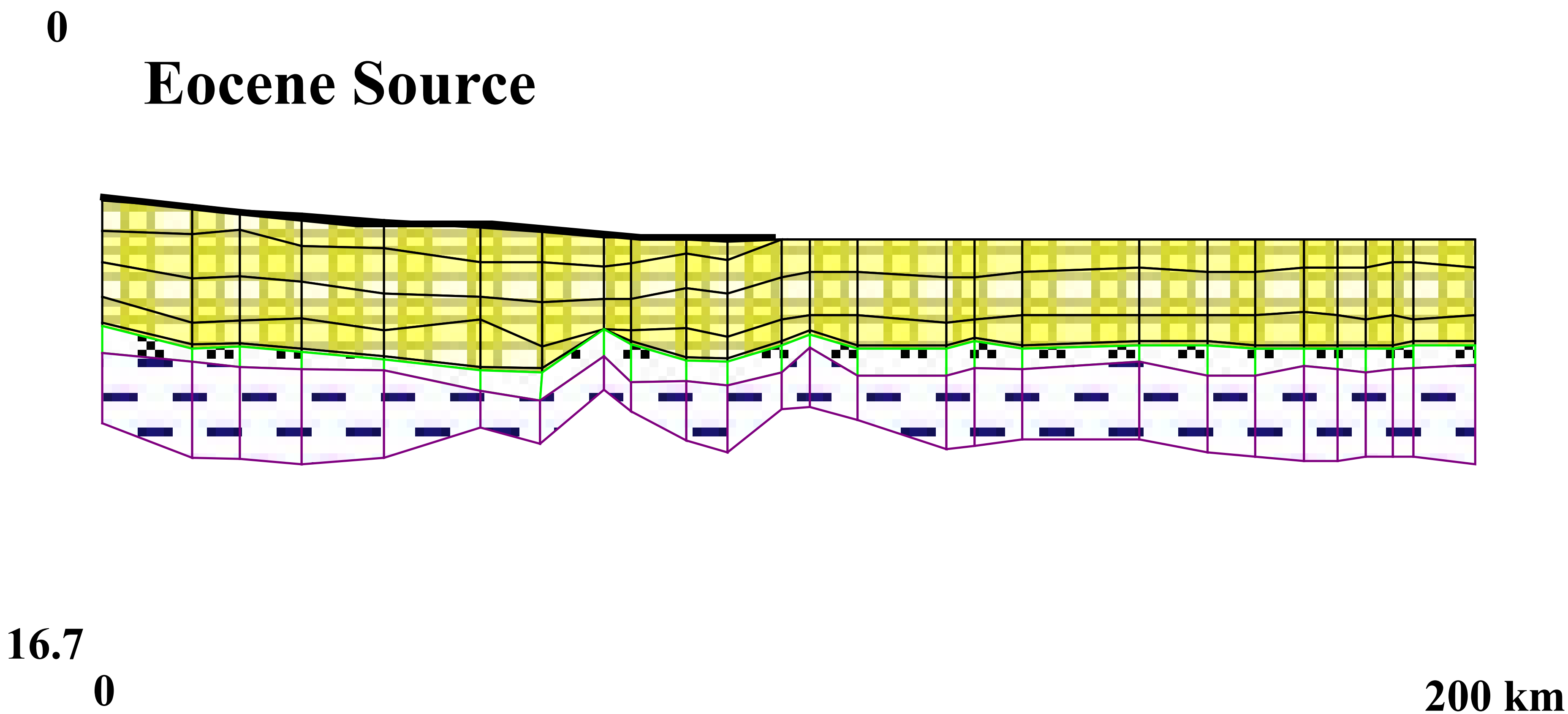
Cathles (2004)

53 Ma



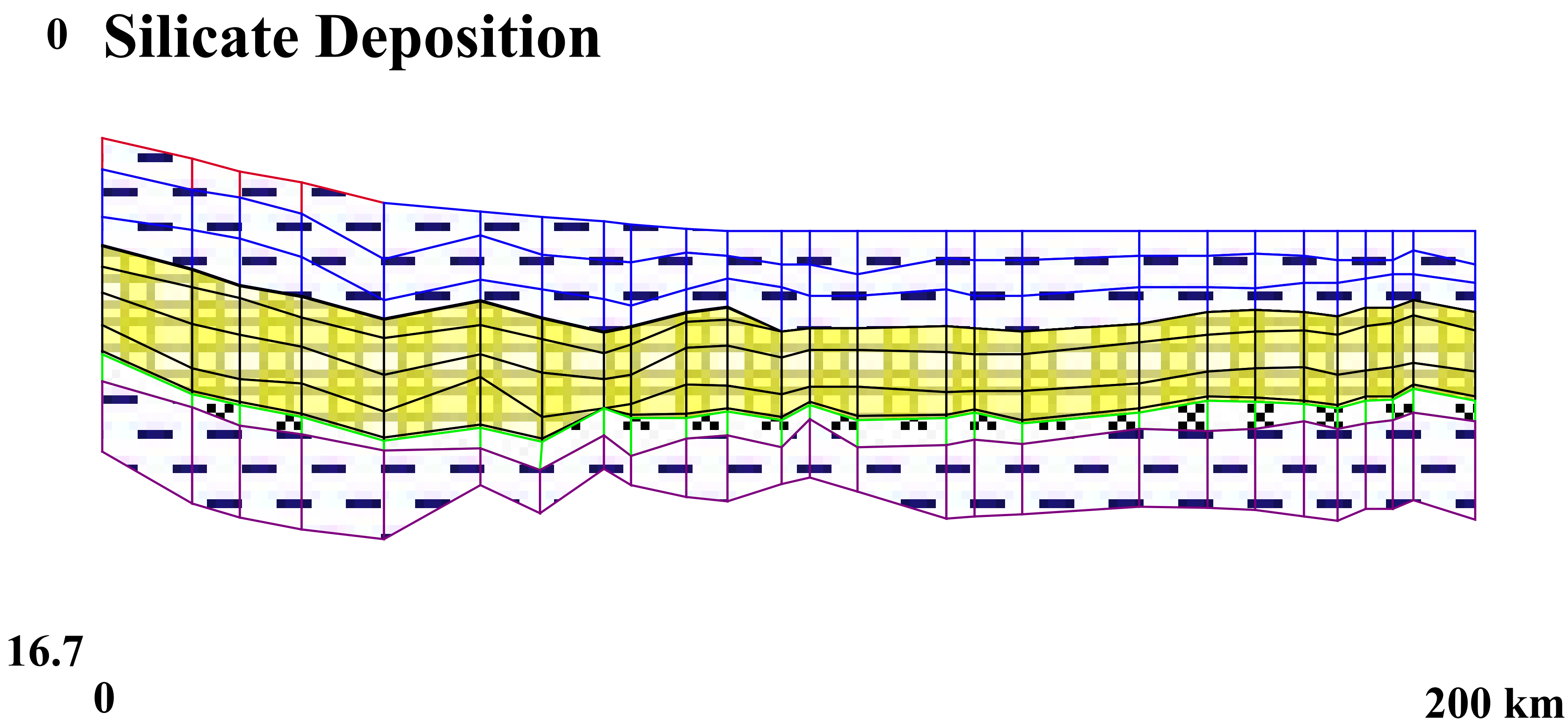
Cathles (2004)

53 Ma



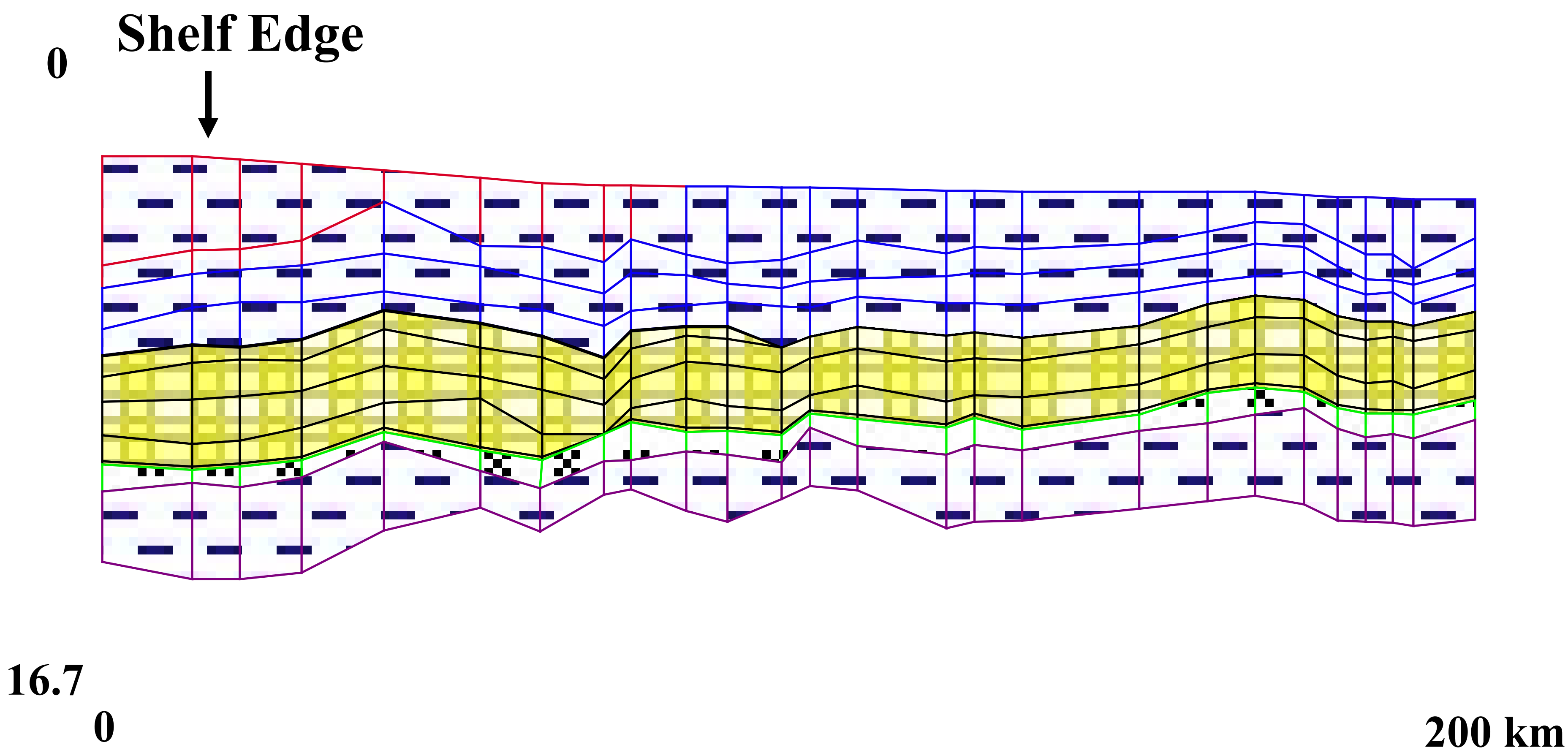
Cathles (2004)

21.5 Ma



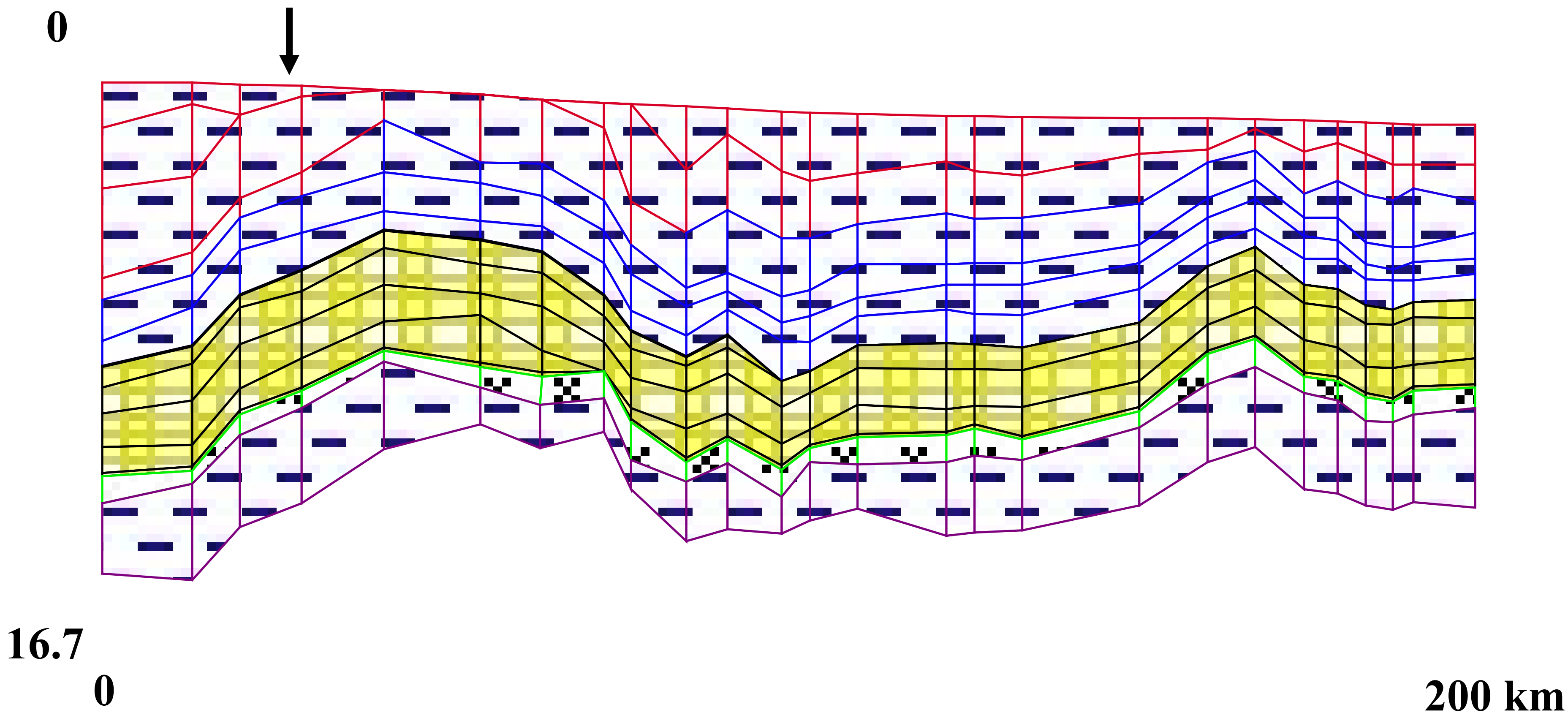
Cathles (2004)

13.8 Ma



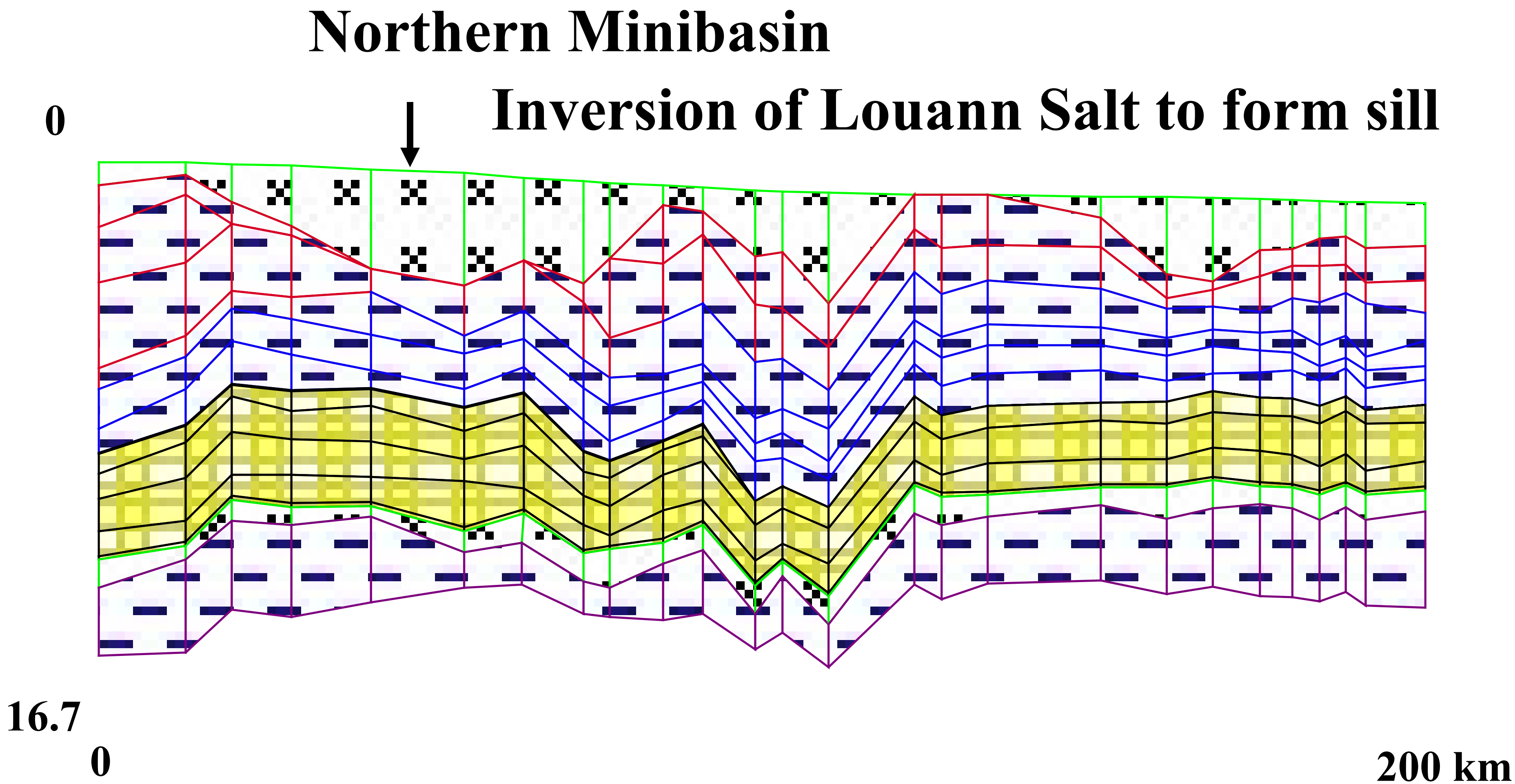
Cathles (2004)

10.6 Ma



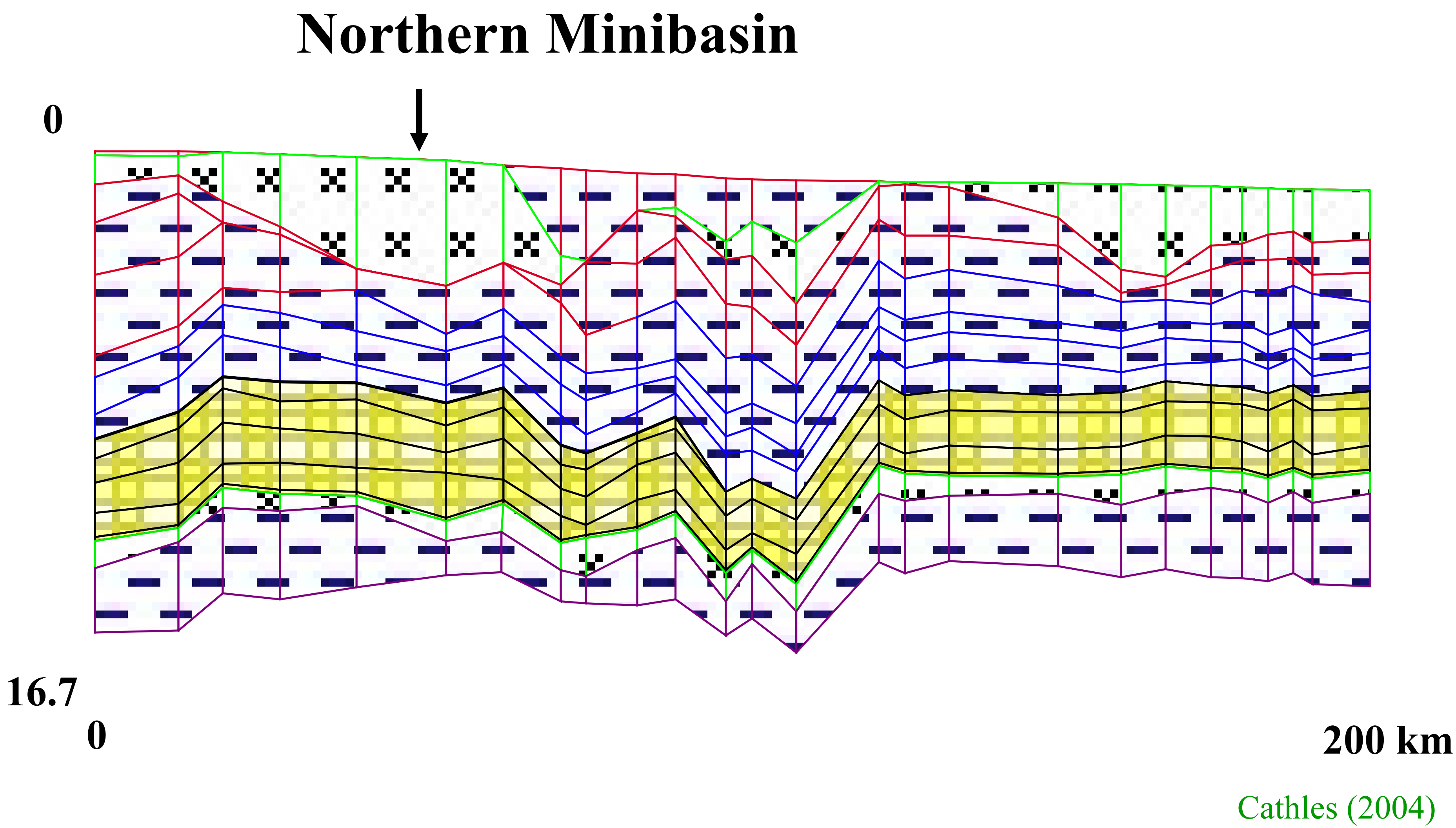
Cathles (2004)

10.5 Ma

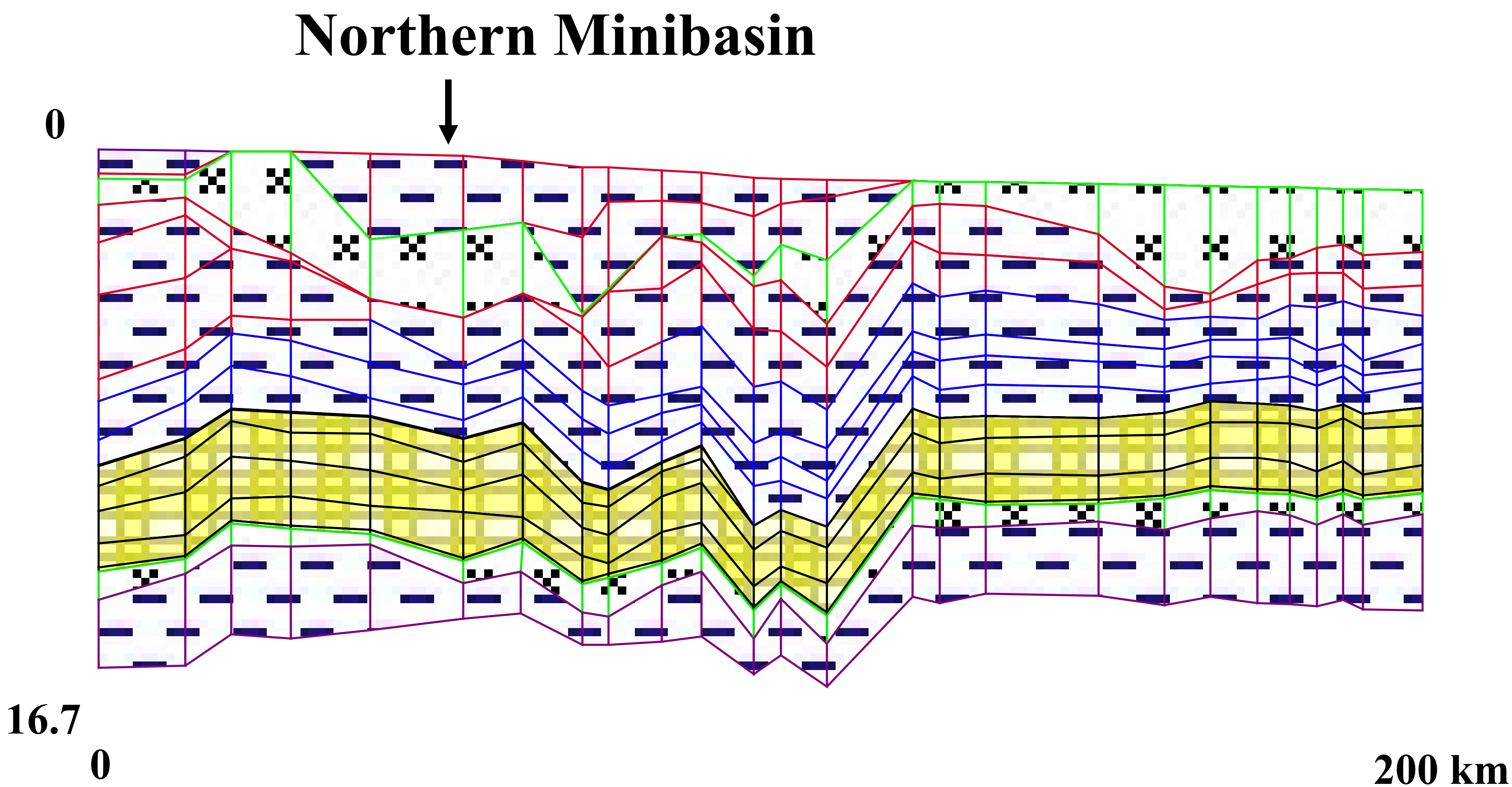


Cathles (2004)

10.1 Ma

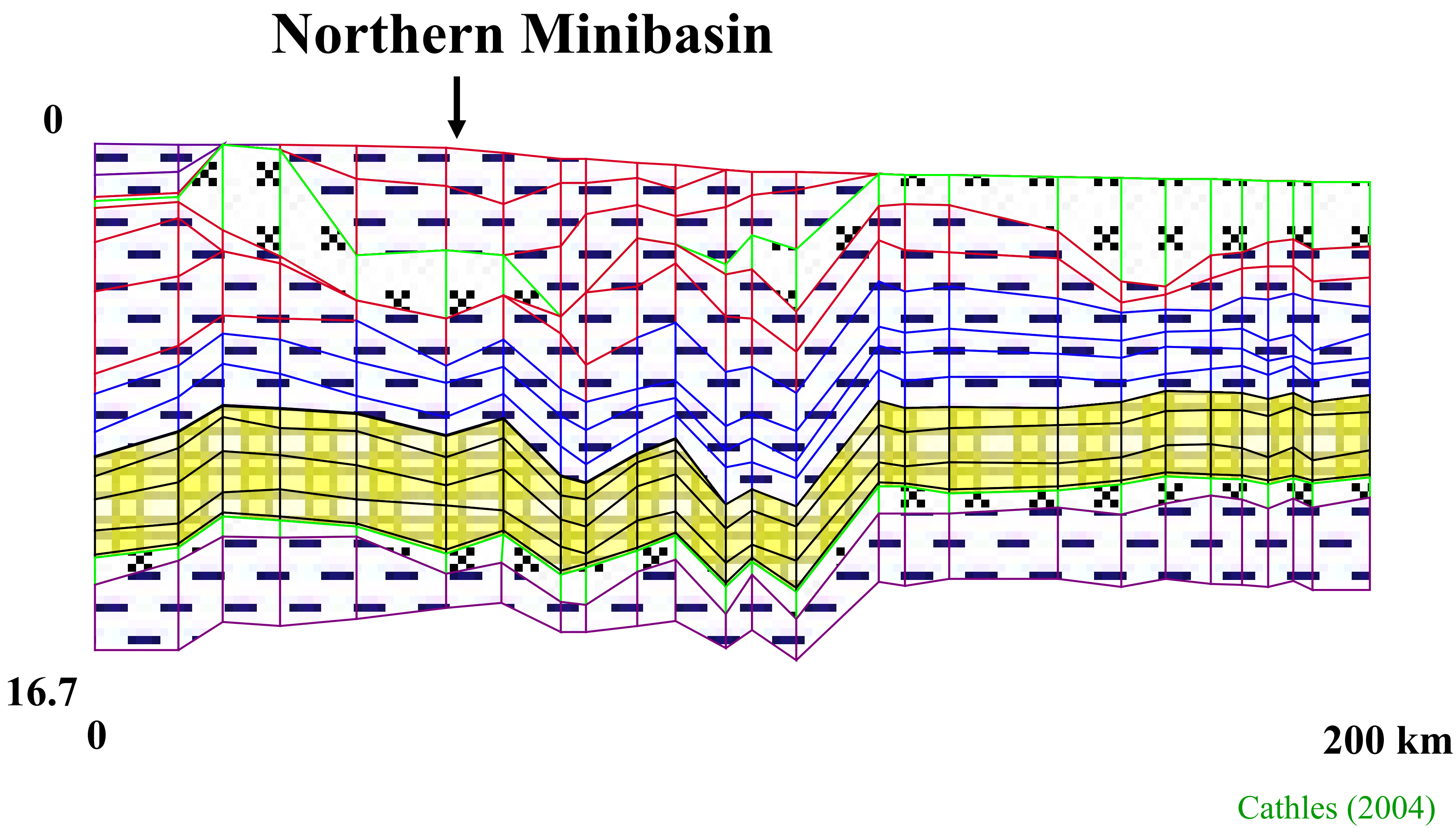


8.8 Ma

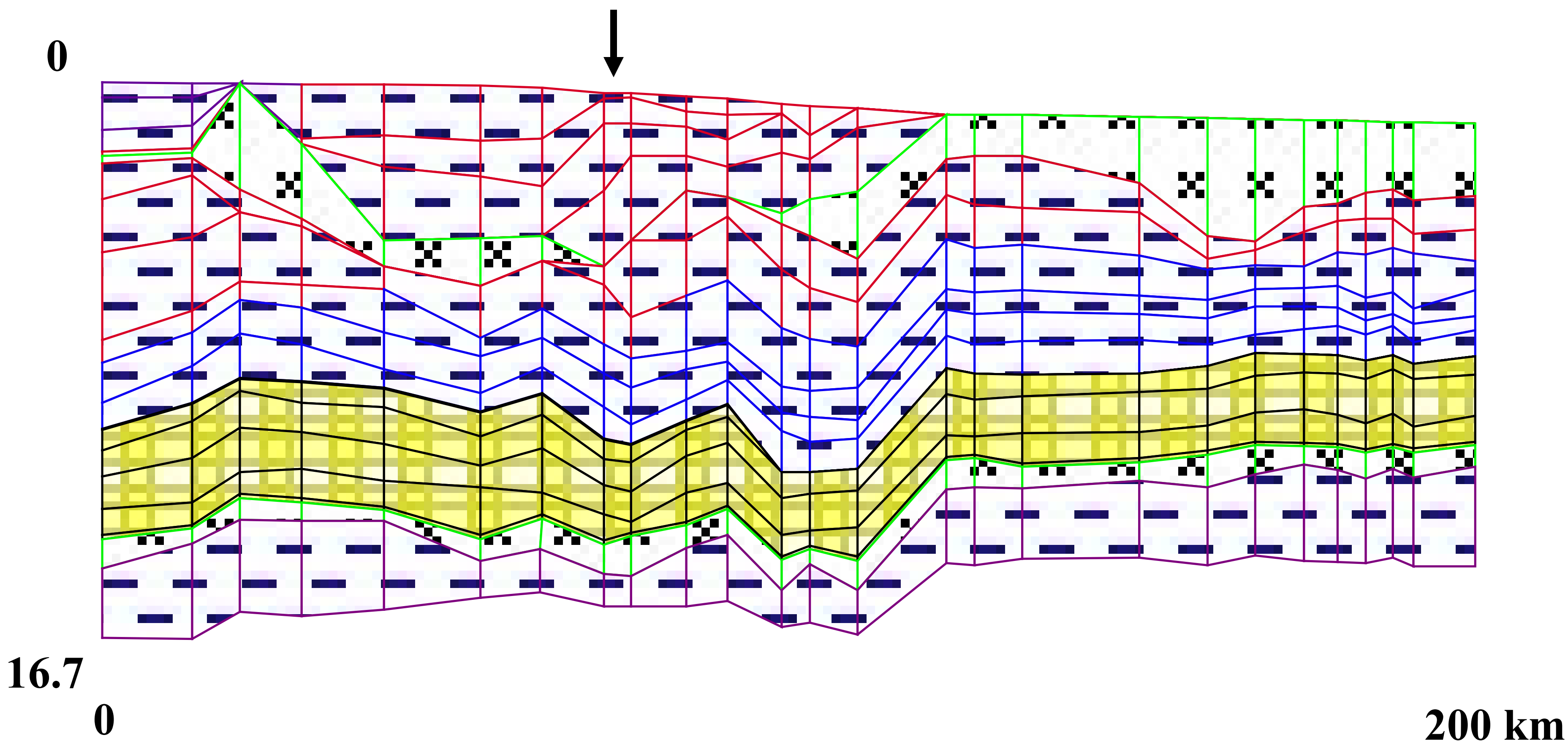


Cathles (2004)

8.2 Ma

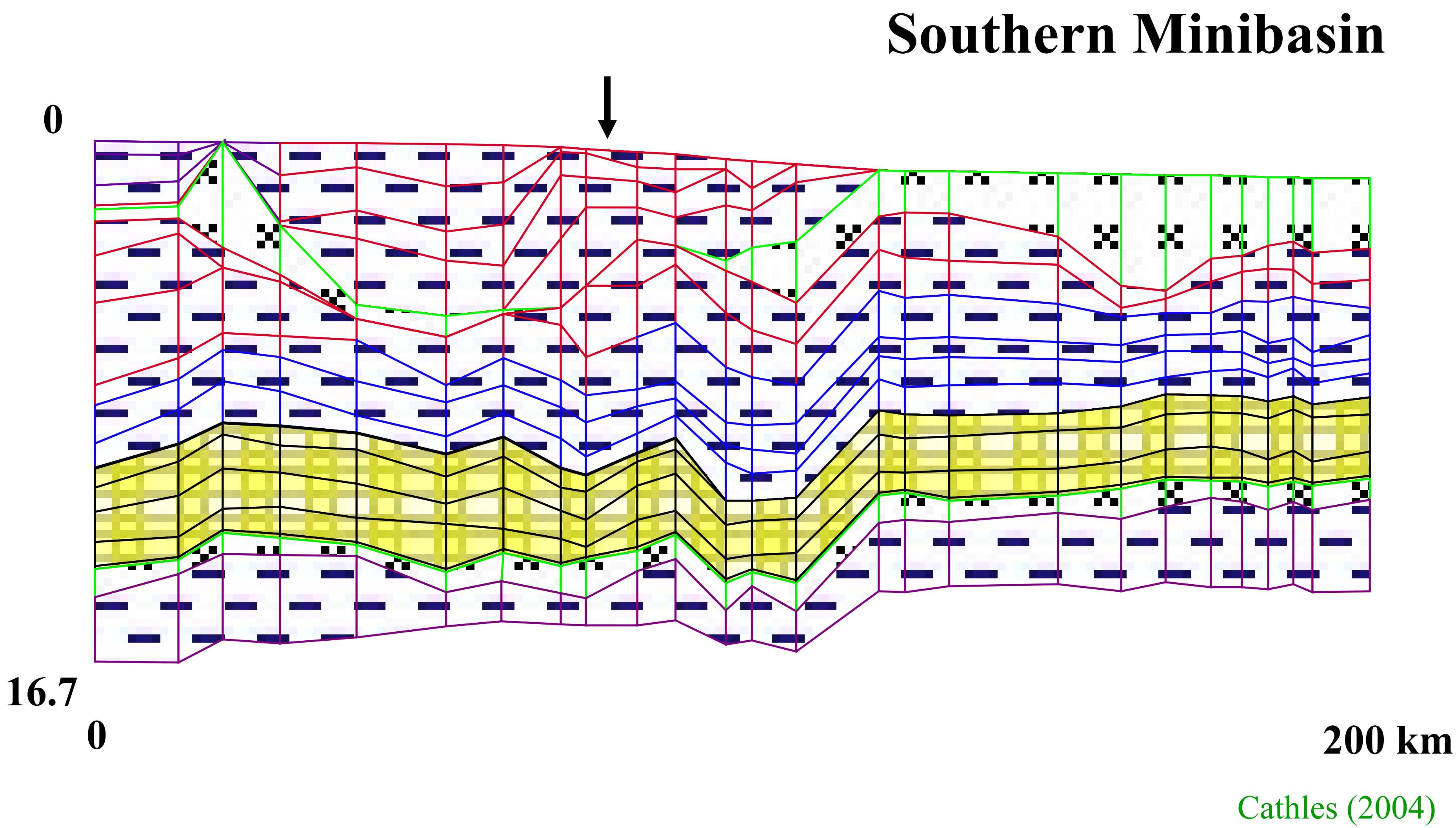


6.3 Ma

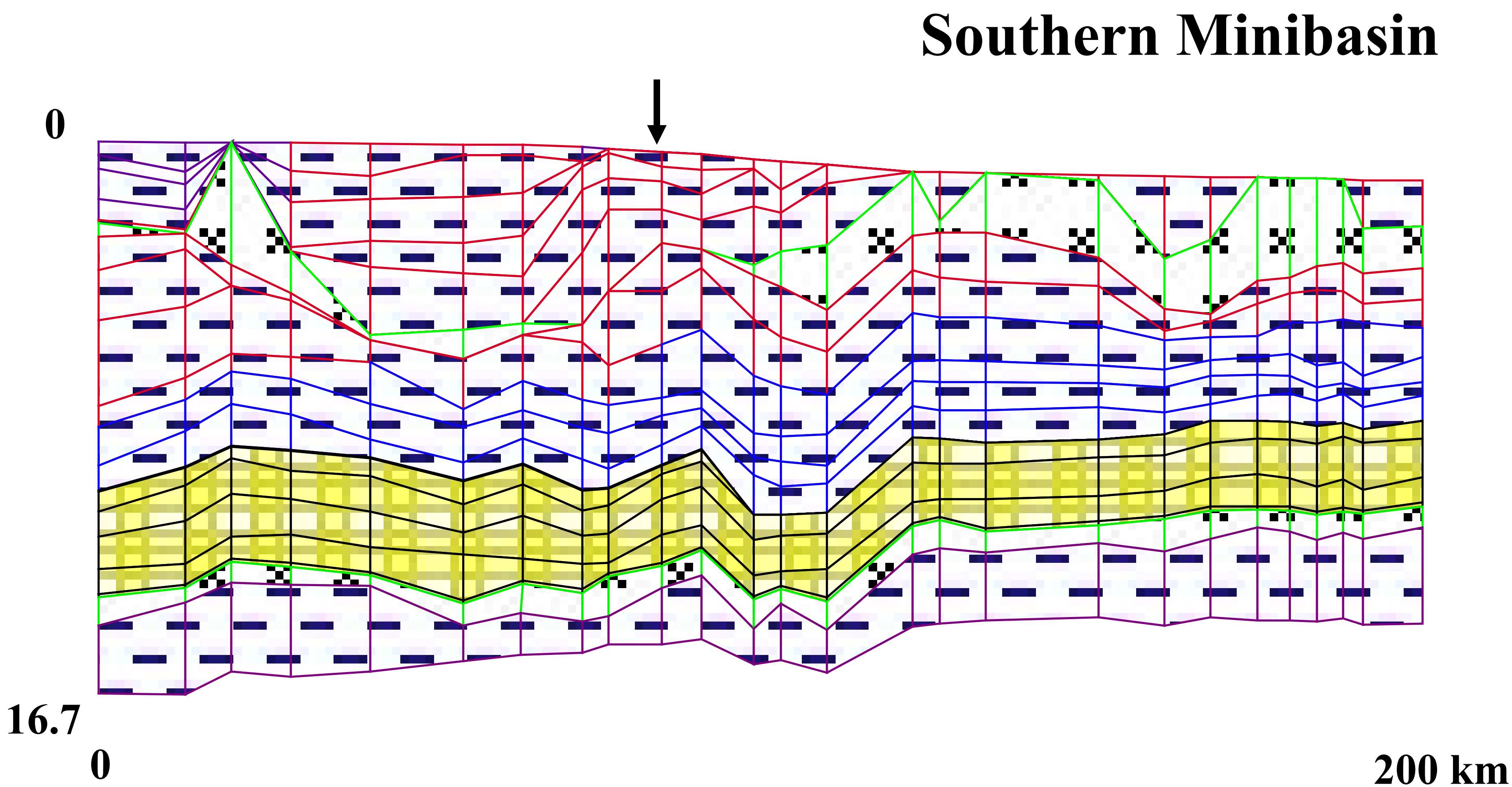


Cathles (2004)

5.8 Ma

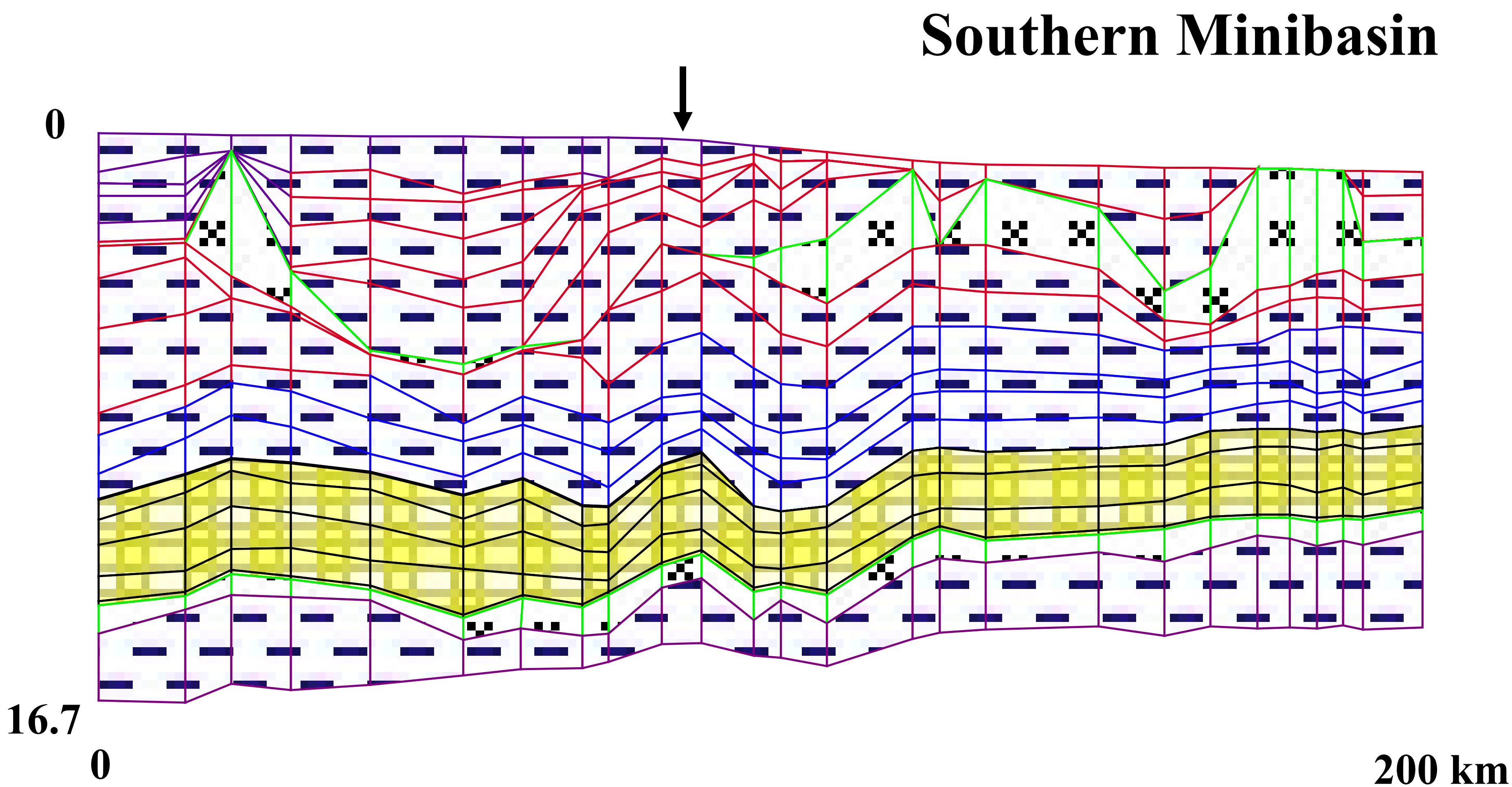


5.5 Ma



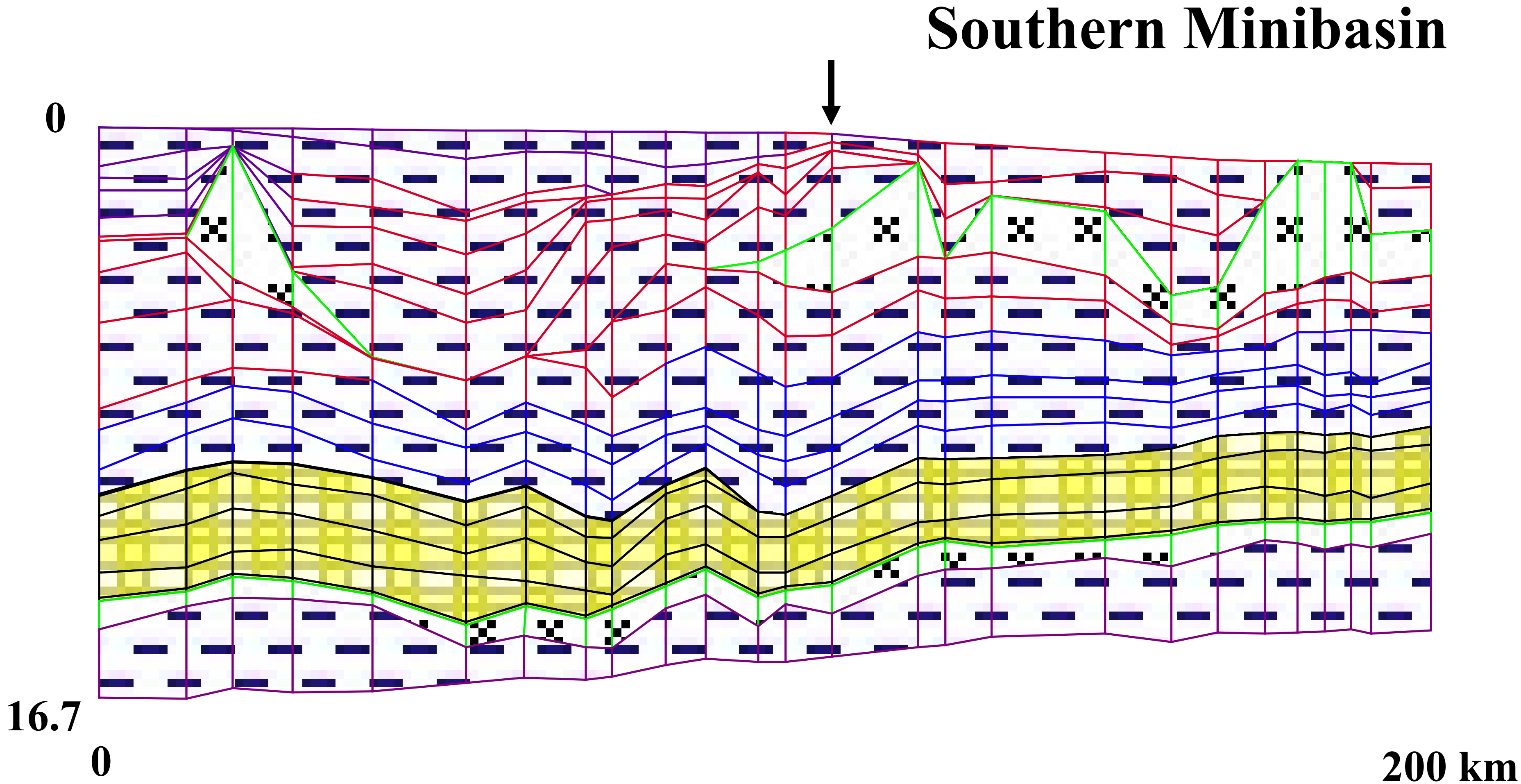
Cathles (2004)

4.2 Ma



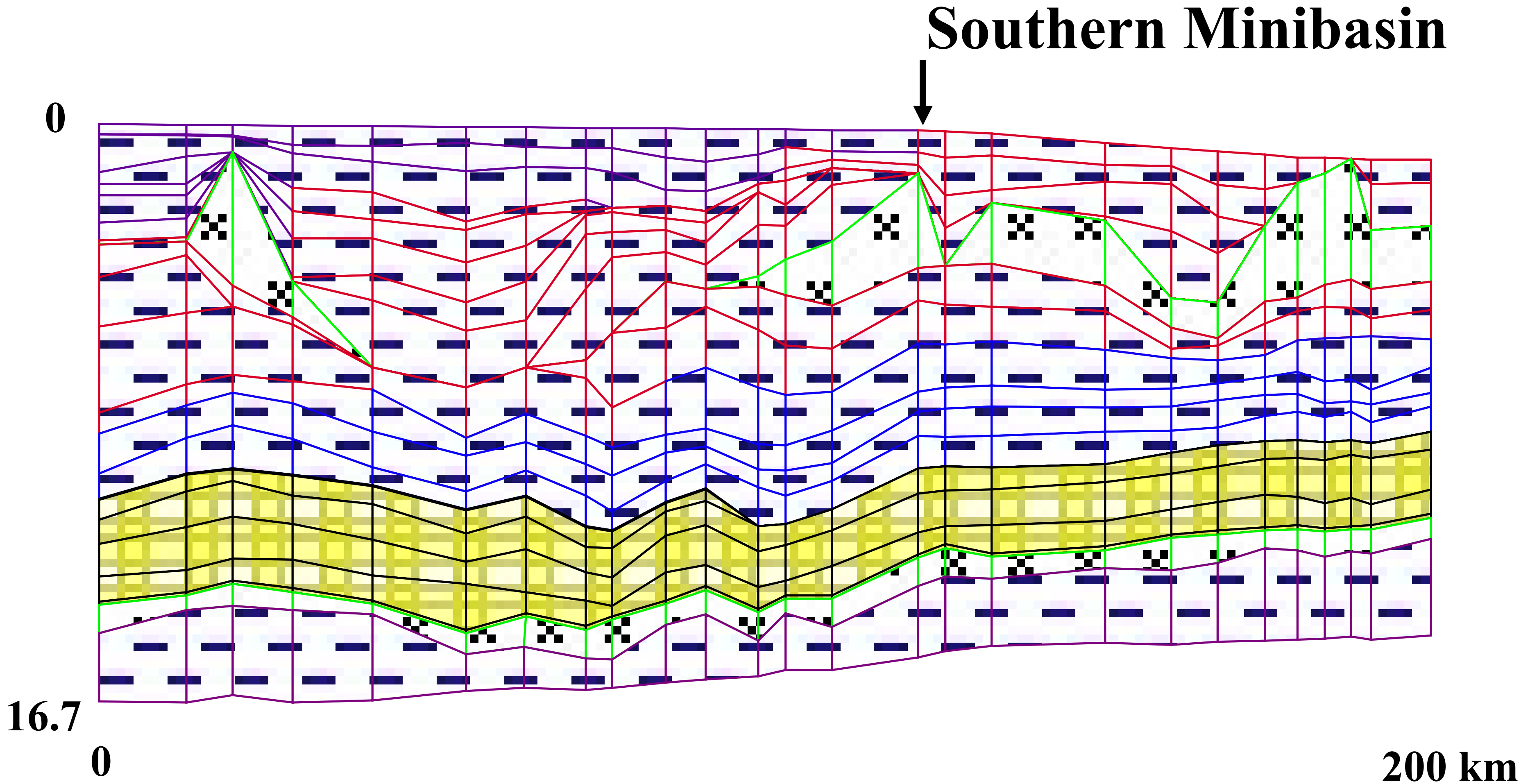
Cathles (2004)

3 Ma



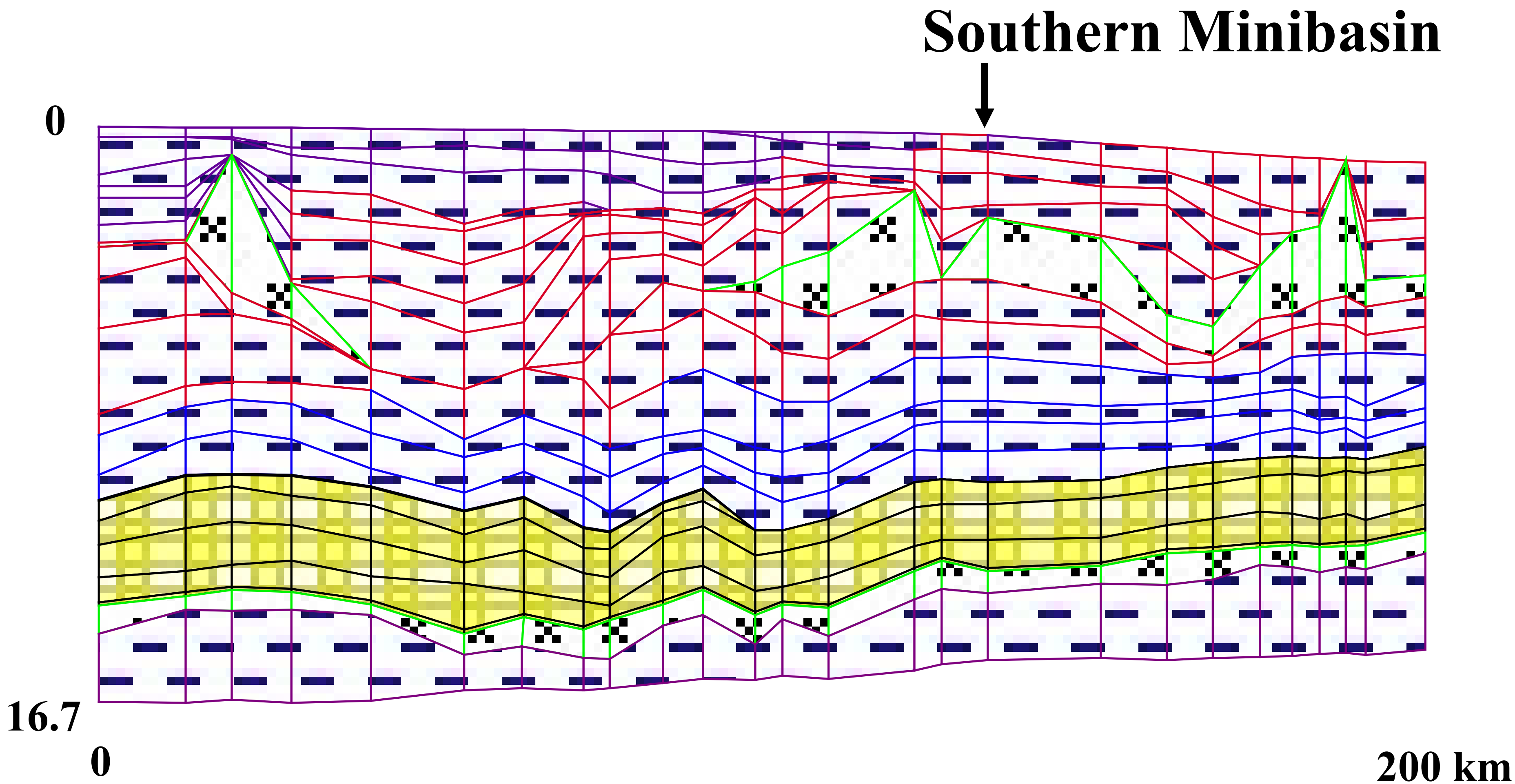
Cathles (2004)

1.4 Ma



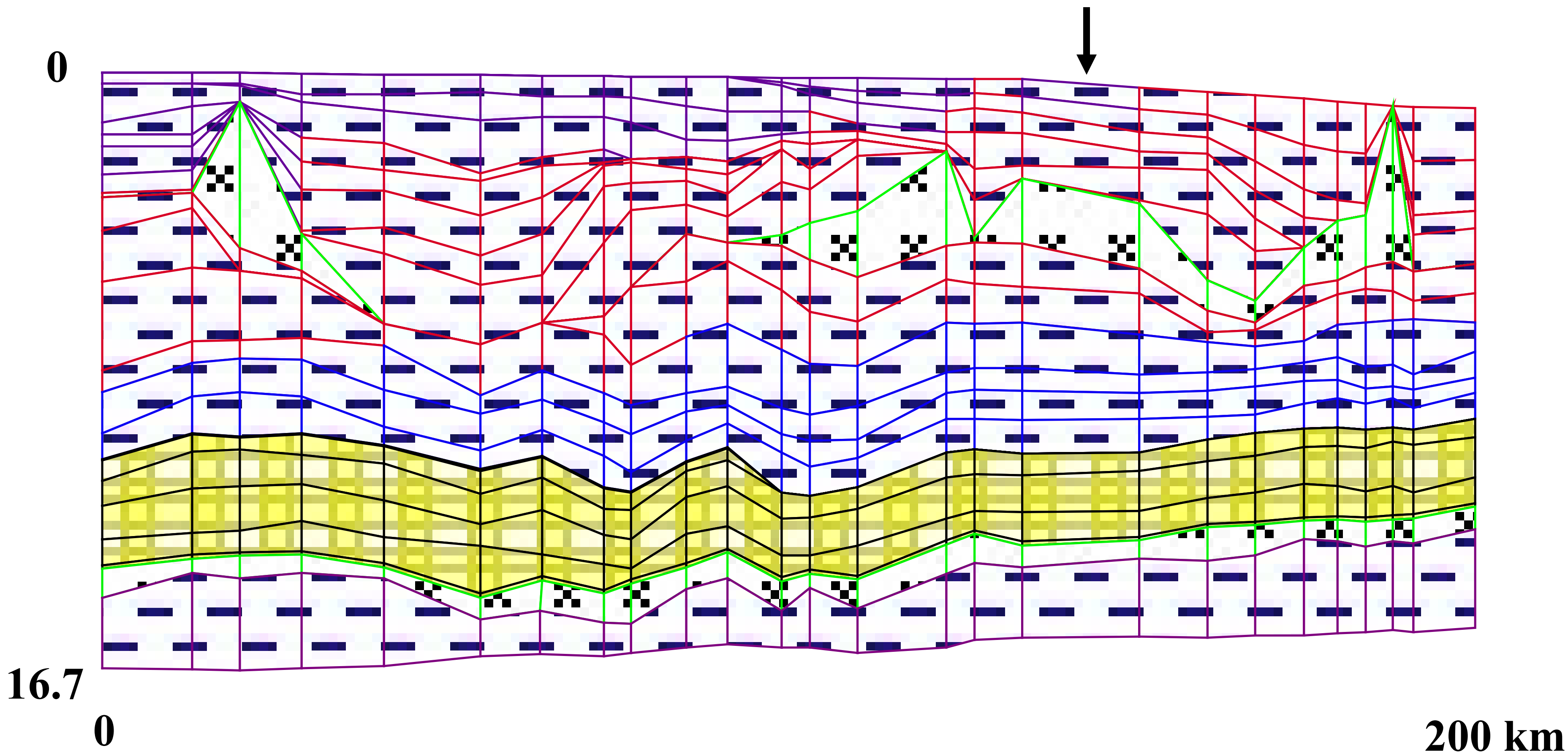
Cathles (2004)

0.95 Ma



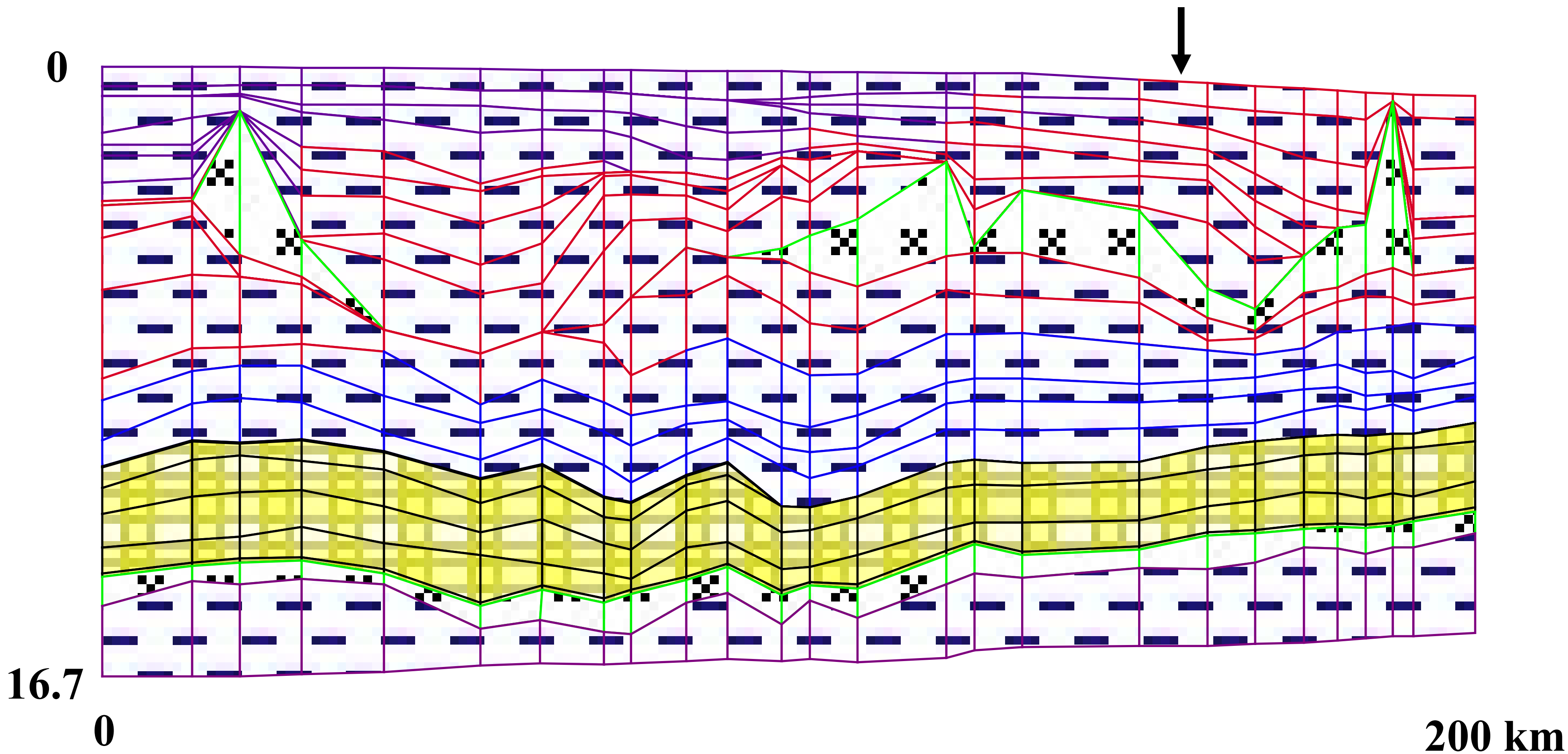
Cathles (2004)

0.5 Ma



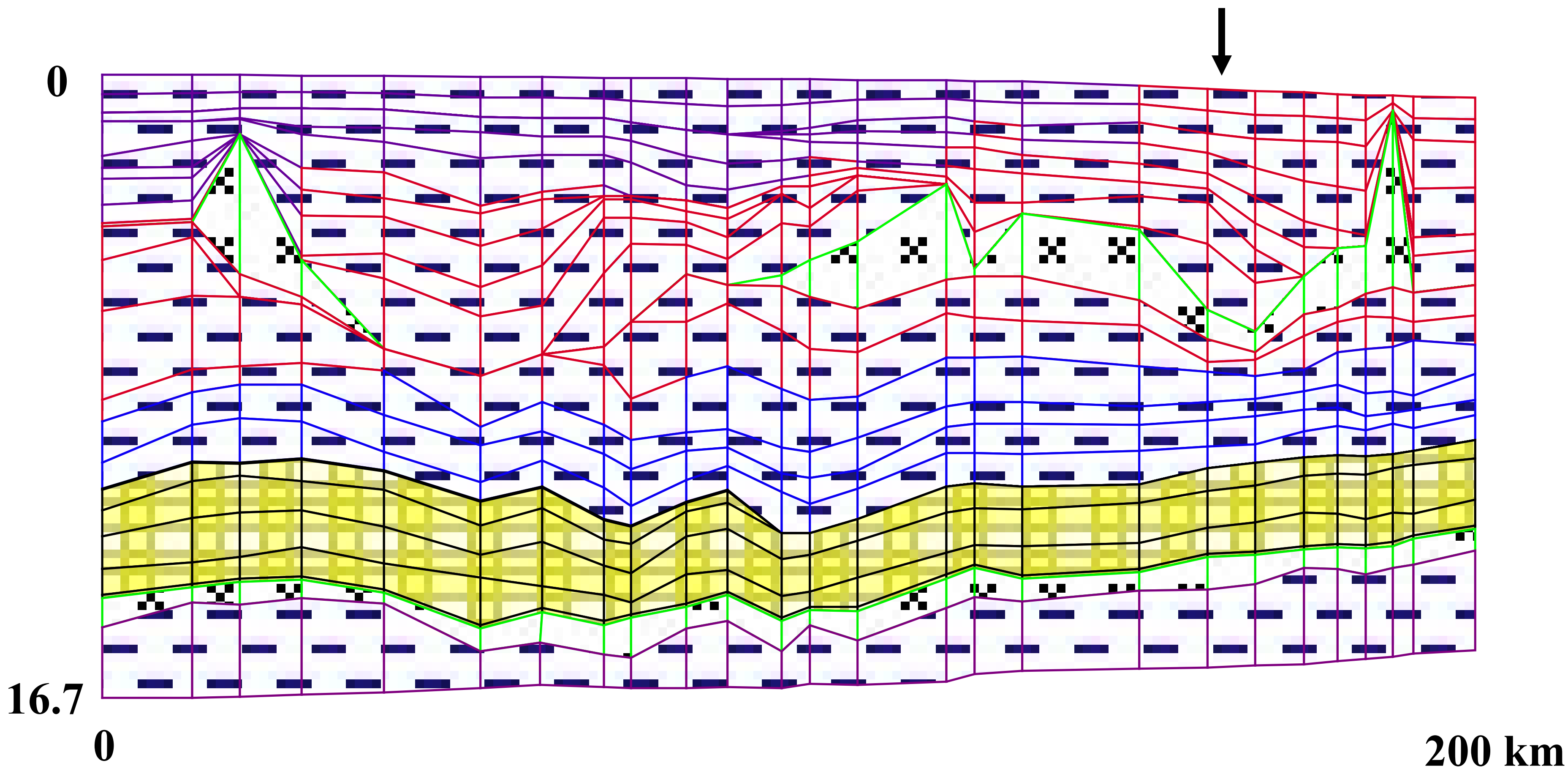
Cathles (2004)

0.25 Ma



Cathles (2004)

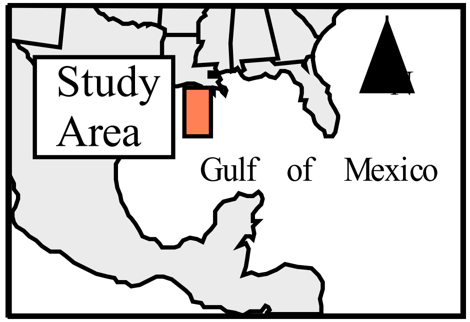
0 Ma

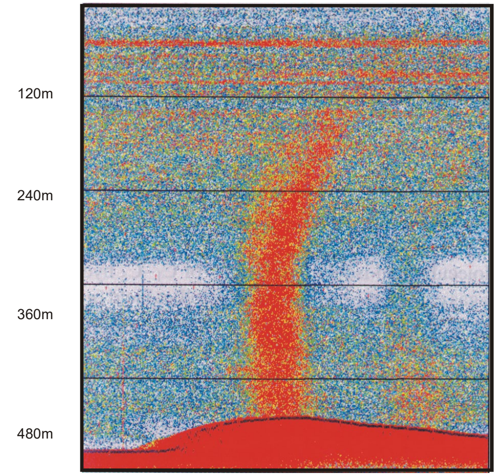


Cathles (2004)

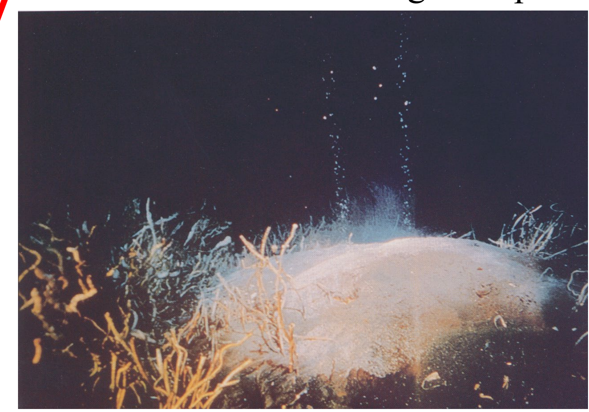
GoM is a massively leaky system

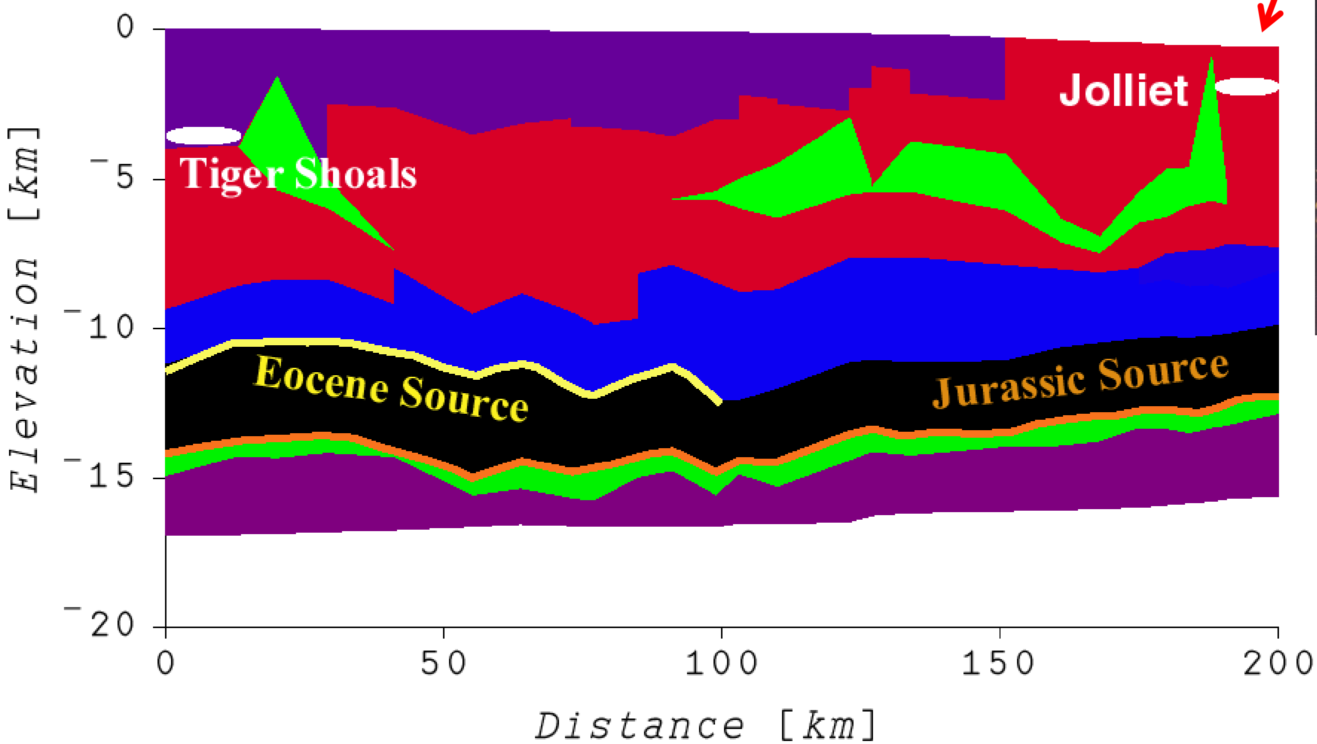
Hydrocarbons maturing and migrating today, pouring out of ~10,000 seeps on the seafloor





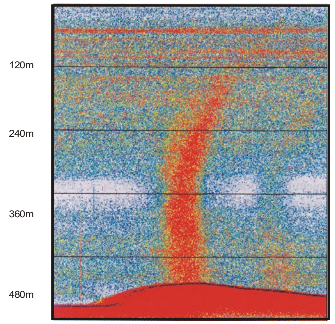
Bush Hill Hydrate Mound and gas seep

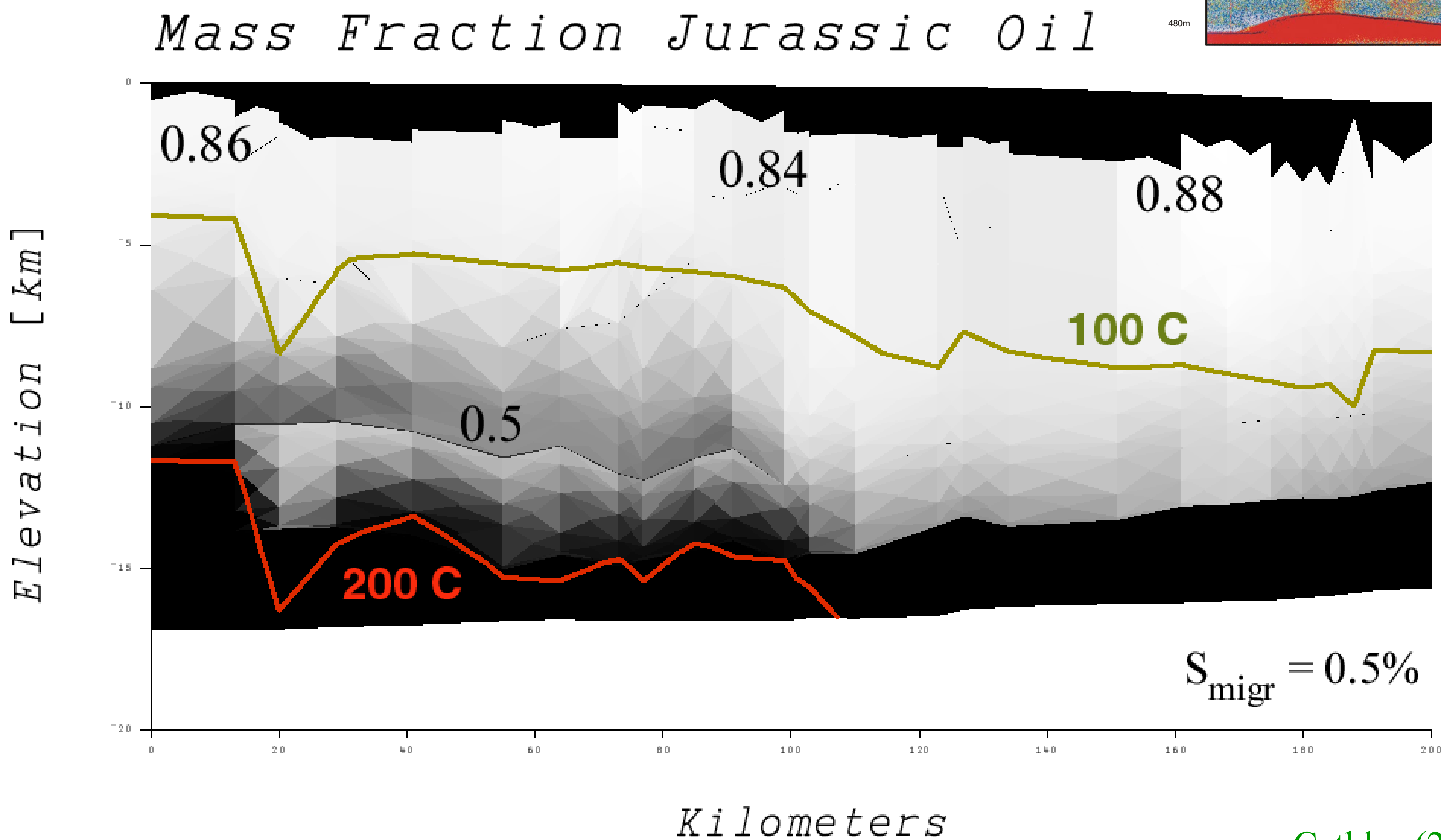




Cathles (2004)

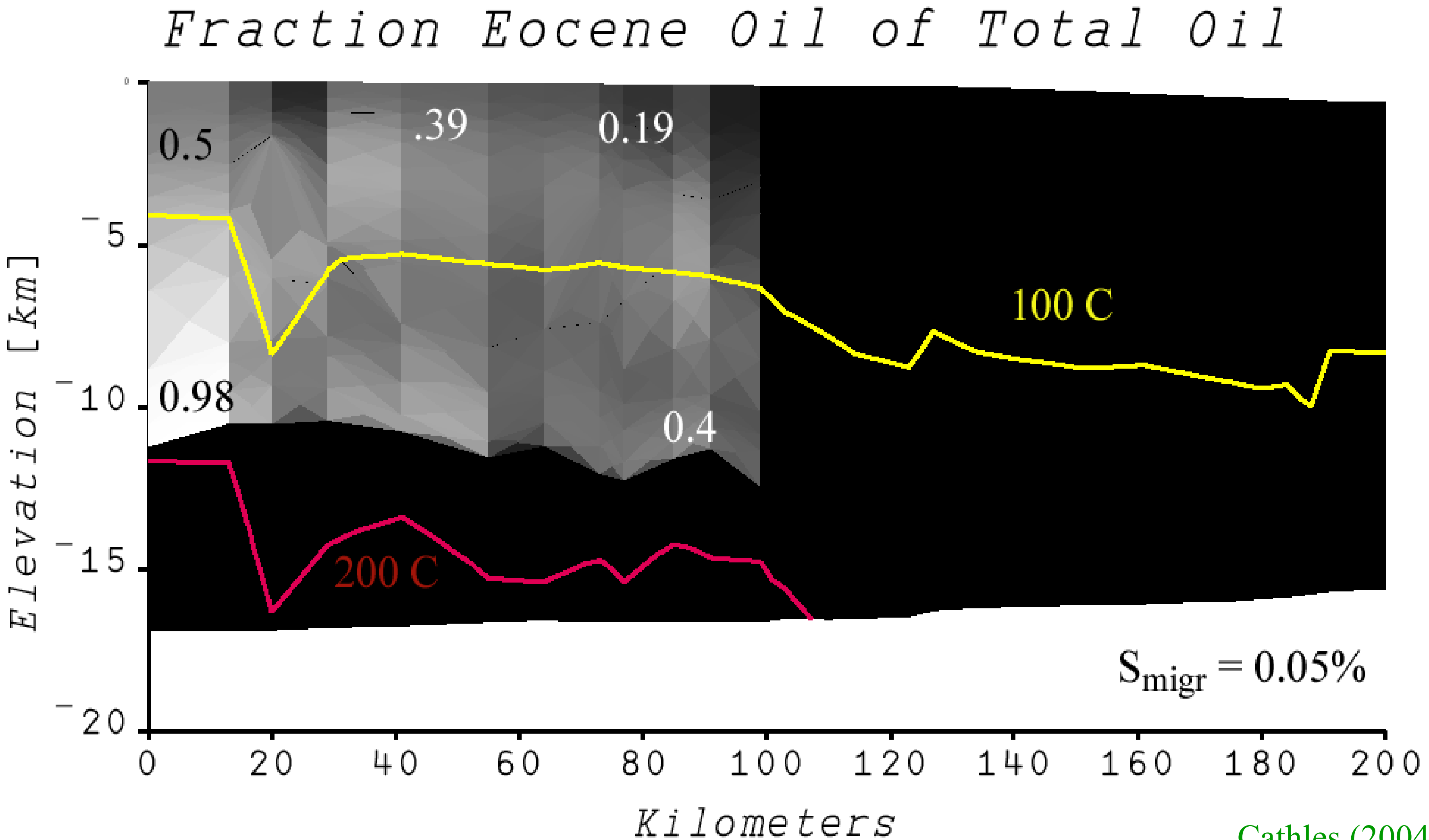
Vent only if S_{migr}<0.5%





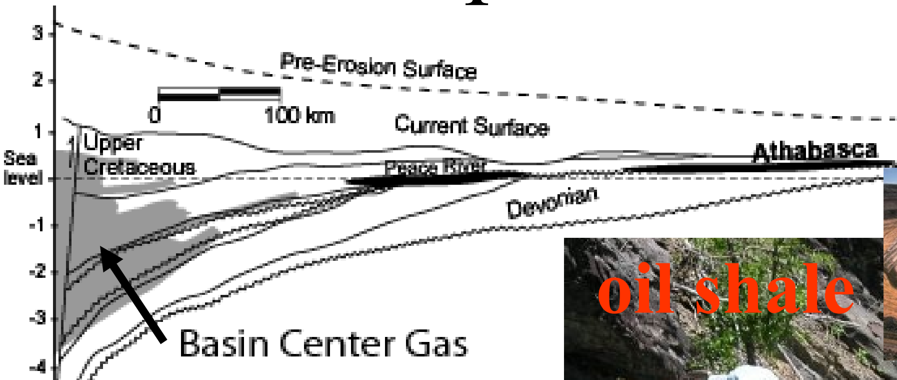
Cathles (2004)

Eocene Oil Dominates if $S_{migr} < 0.05\%$

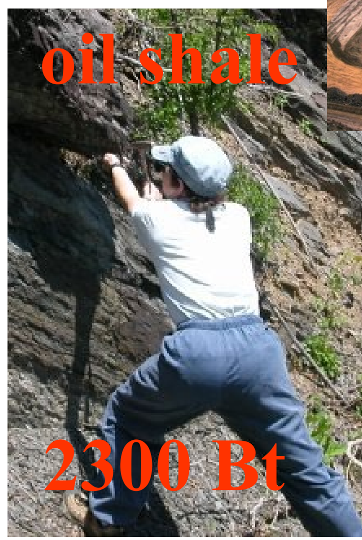


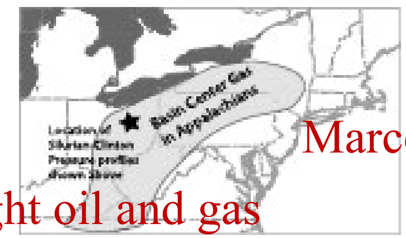
Cathles (2004)

Source and Spill are main "new" resources

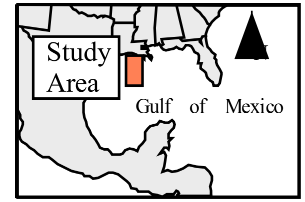


1720 Bt w/ coal bed CH4





Tight oil and gas

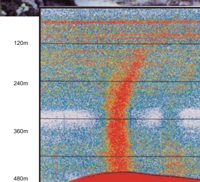


125 x 202 km Corridor

184 Bto	Generated
Source → **37**	**Retained in source**
15	In Migration Pathways
1.4	Proven Resources
spill → **131** **~1000 x 10^9 bbls**	**Vented** = 0.43 WR

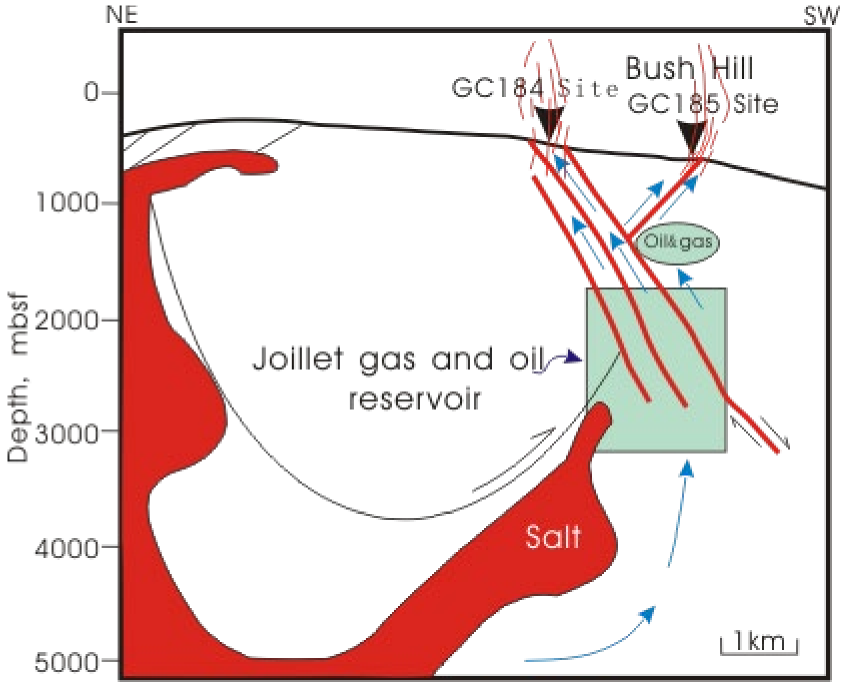
Conventional

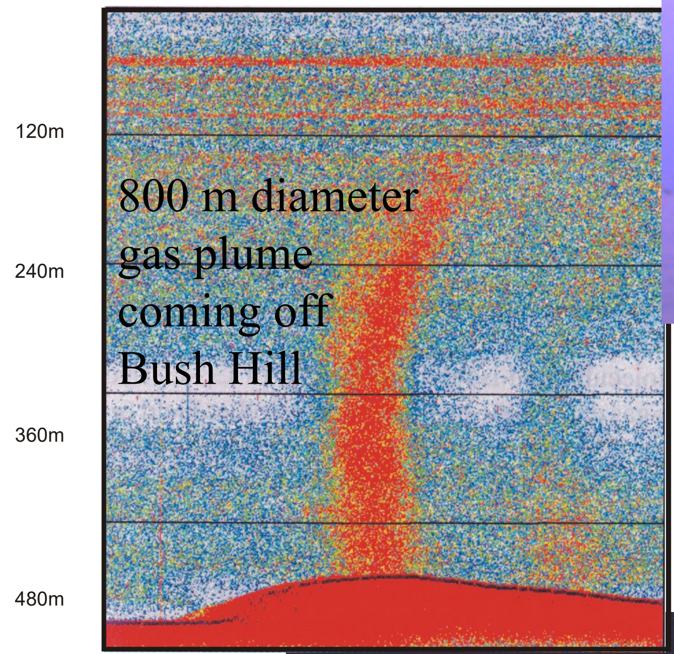
$$\frac{184}{870 \text{ Resource Base}} = 21\% \text{ RB}$$

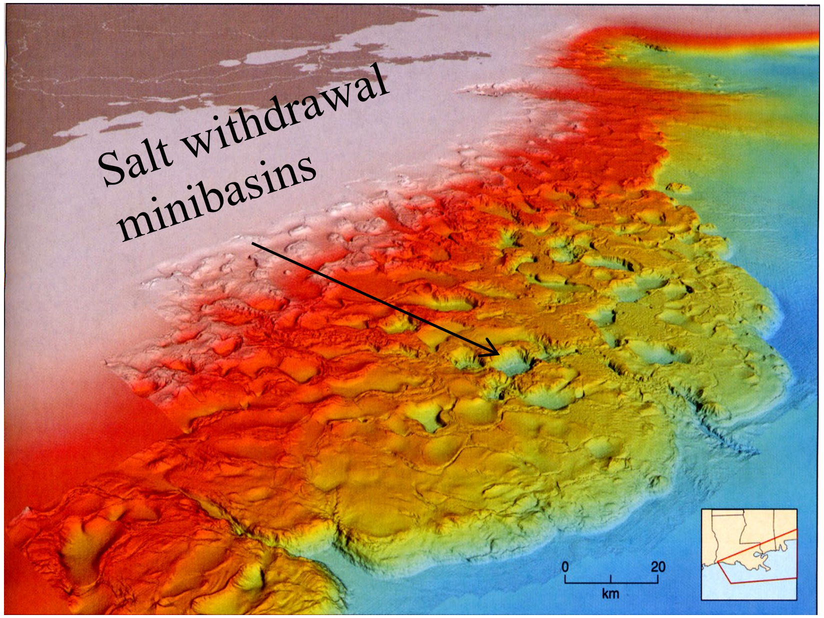


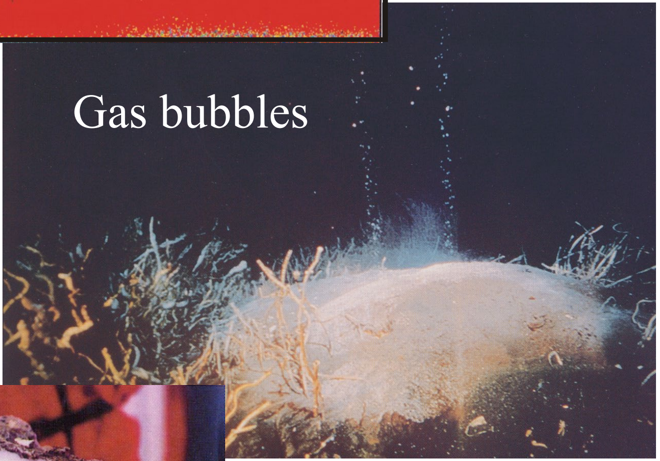
the ice that burns

Cathles (2004)



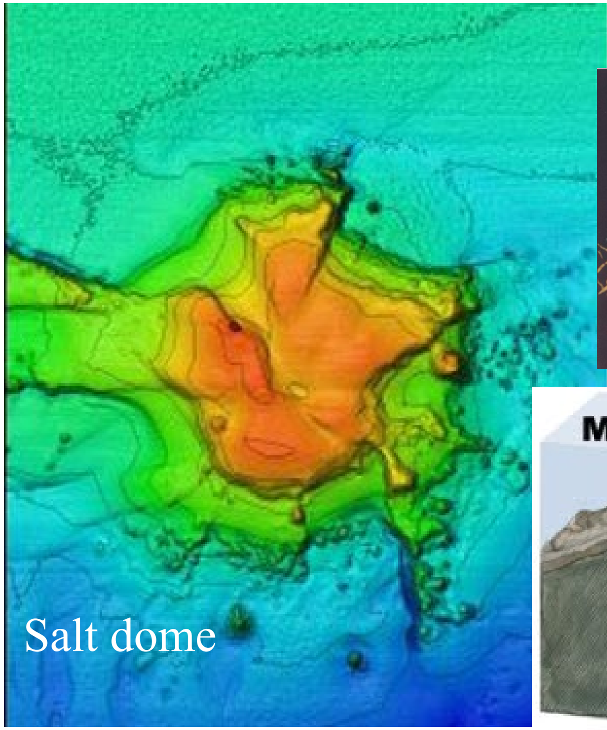


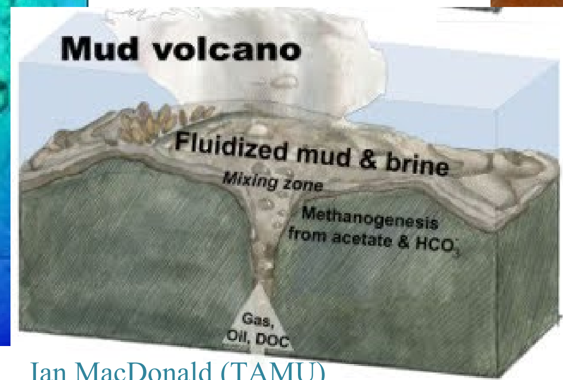


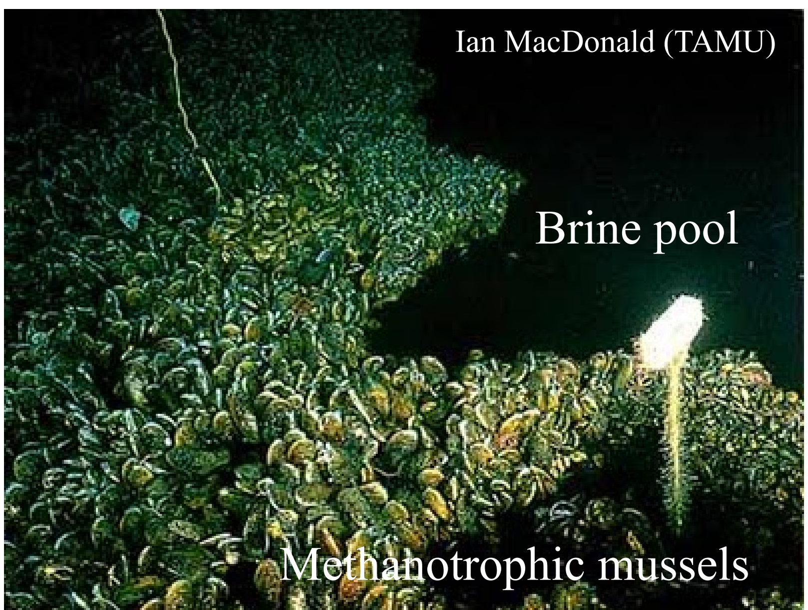


Gas hydrates-
frozen gas
The ice that burns

Images mainly from the Gulf of Mexico








Ian MacDonald (TAMU)
Small oil droplets
adhering to hydrate


Mineral chimney and microbe mats
http://i.livescience.com/images/090407-deep-vent-02.jpg


Ian MacDonald (TAMU)


Madrepora coral
Mississippi Canyon
Oceanexplorer.noaa.gov


Callogoria coral; cup coral

Azerbaijan

Mud volcanoes, stratigraphic inversion

HC overpressuring makes sediments quick

Azerbaijan dramatic example

In Azerjaijan mud volcanoes are literally inverting the stratigraphy

Gas pipe- when gas can leave source
Mud volcano- when it can't

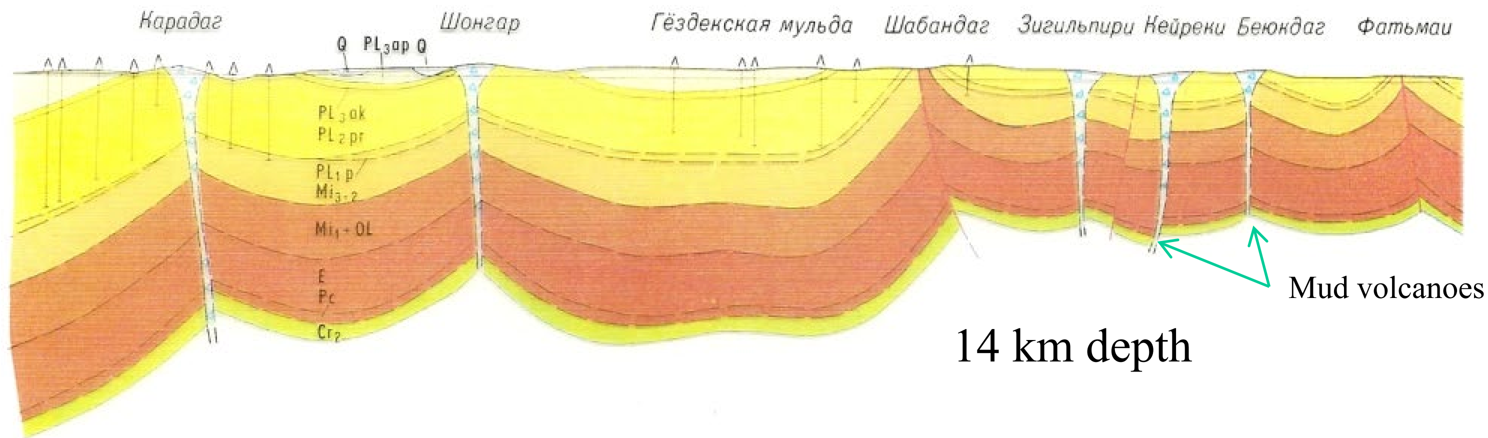
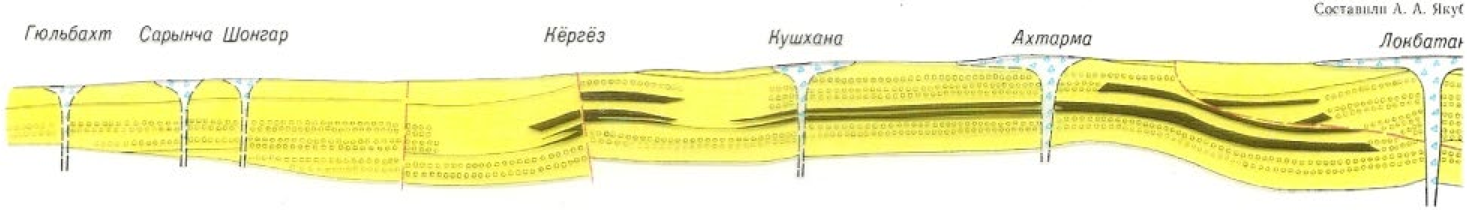


Рис. 6. Региональный геологический профиль через грязевые вулканы Карадаг — Шонгар — Беюкдаг.
Составили А. А. Якубов, А. А. Ализаде, М. М. Зейналов.

Рис. 7. Региональный геолог
бахт — Кушхана — .
Составили А. А. Якуб



Mud Volcanoes of the Azerbaijan SSR, Publ. House of the Academy of Sciences Azerbaijan, Baku, 1971

Mud volcano 400-500 m high and 1-3.5 km diameter

Mud breccia outbursts with gaseous jets
Entrained fragments of rock 1-2 m diameter

Рис. 213. Геологический профиль через грязевой вулкан Тоурагай.

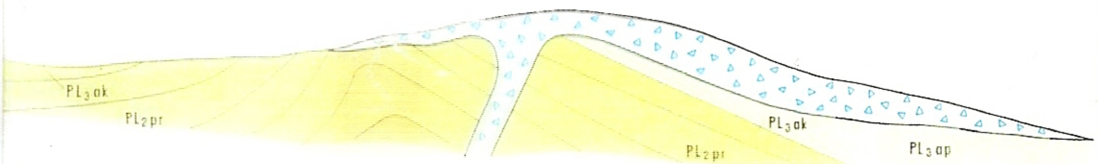
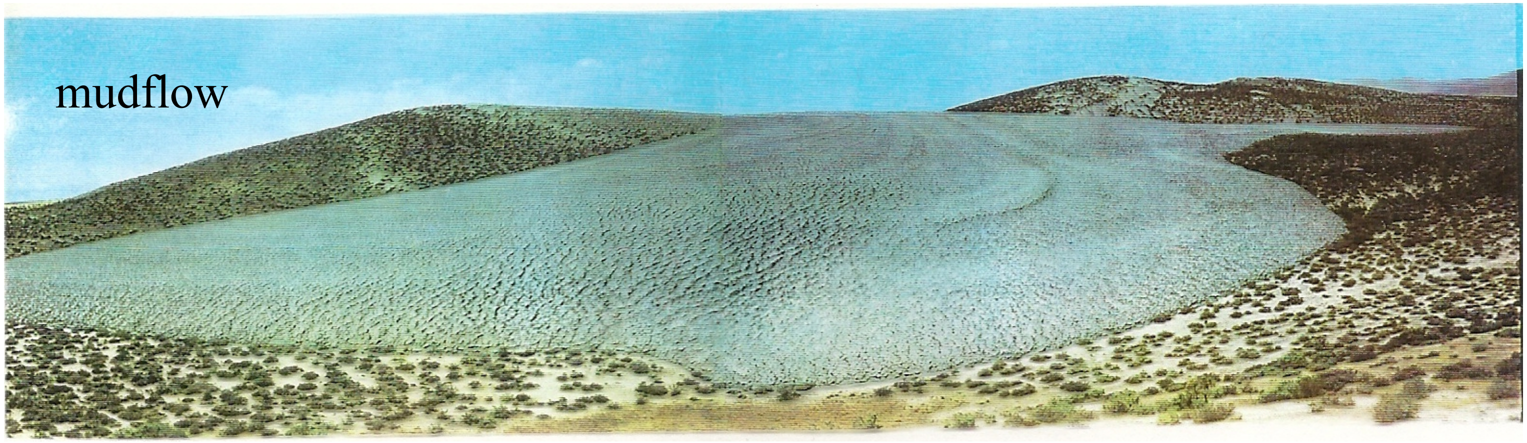
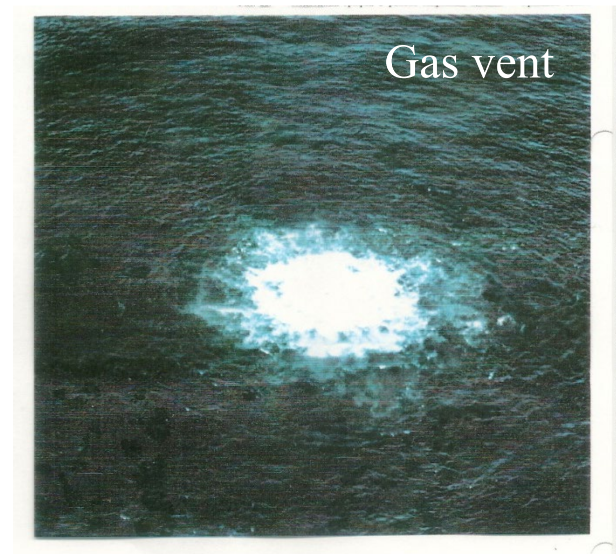


Рис. 211. Грязевой вулкан Тоурагай. Общий вид (аэрофотосъемка).

Рис. 212. Грязевой вулкан Тоурагай. Общий вид.

Mud Volcanoes of the Azerbaijan SSR, Publ. House of the Academy of Sciences Azerbaijan, Baku, 1971





Triad of oil, gas, and diapiric structures
10 to 13 year eruption cycle
Eternal methane fires (1000 yrs)

Mud Volcanoes of the Azerbaijan SSR, Publ. House of the Academy of Sciences Azerbaijan, Baku, 1971

Unconventional resource

Big resources = source and spill

184 Bto	Generated
37	**Retained in source**
15	In Migration Pathways
1.4	Proven Resources
131 **~1000 x 10^9 bbls**	**Vented**

Source

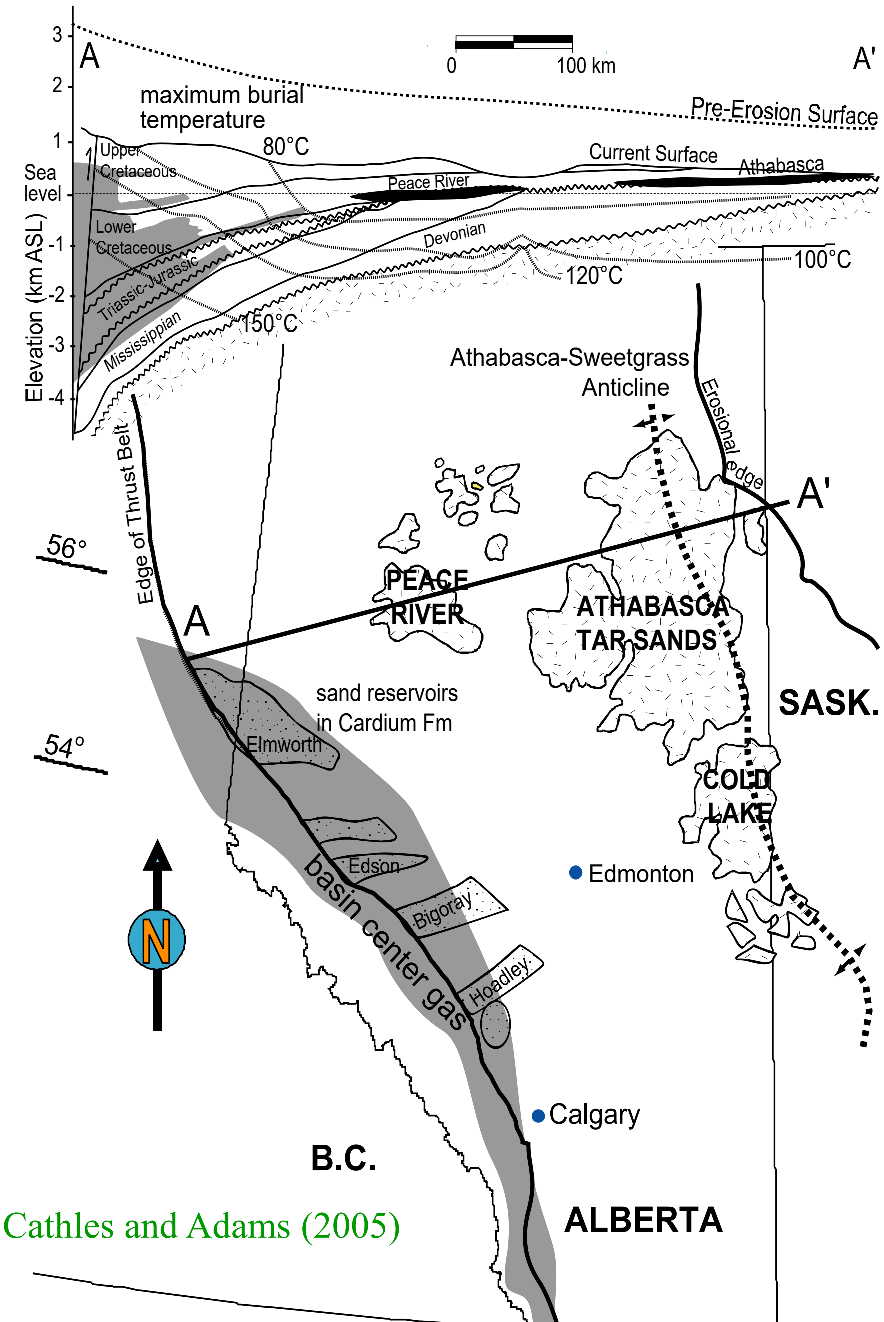
Conventional

spill

What are scientists saying about resources?...

Unconv. #1: Tar Sands

11% Rogner's RB of 870 Gto



Cathles and Adams (2005)

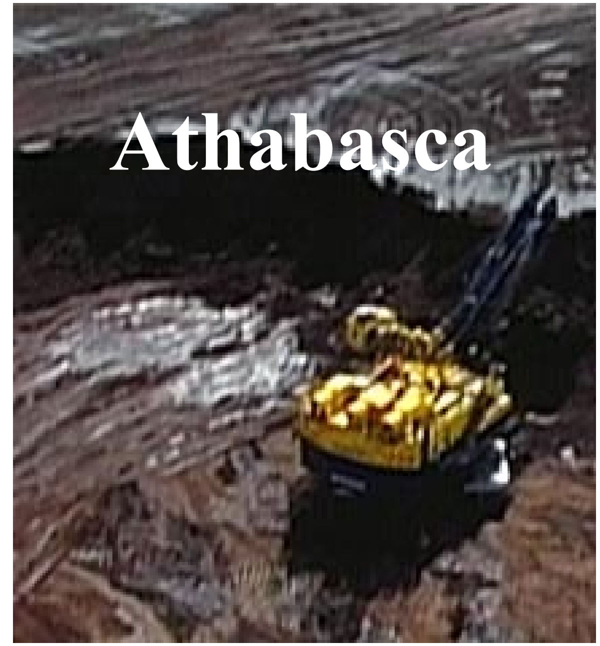


TABLE 5.9

Heavy oils and tar sands (in millions of barrels)

Craig et al. (2001)

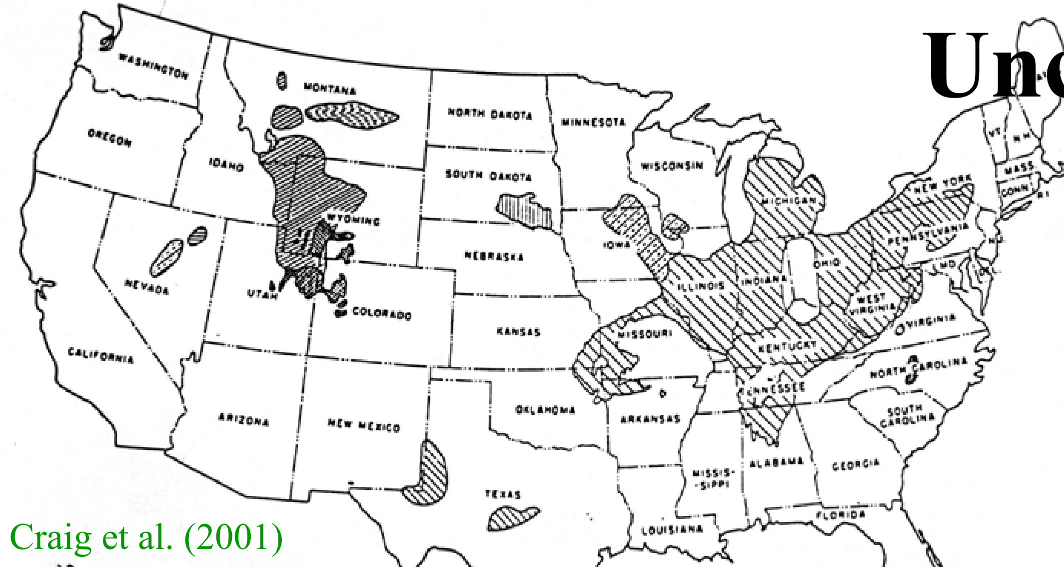
Country	*Oil in Place*	*Recoverable*
Canada	2,950,200	213,340
Venezuela	700,000–3,000,000	500,000
United States	77,160	30,065
Former Soviet Union	630	30
Middle East	50,000–90,000	4700
TOTAL	3,777,990–6,117,990	748,135

11% Rogner's RB of 870 Gto

100 Gto

Unconv #2: Oil Shale

"the rock that burns"



Craig et al. (2001)

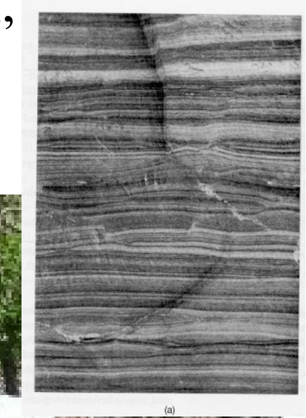


TABLE 5.10

Shale oil resources of the world, in 10^9 barrels in terms of oil content

Continent	*Identified Resources*		*Hypothetical Resources*		*Speculative Resources*	
Gallons of oil per tons of shale	*25–100*	*10–25*	*25–100*	*10–25*	*25–100*	*10–25*
North America:						
U.S.—Green River Shale	418	1400	50	600	—	—
U.S.—Chattanooga Shale	—	200	—	800	—	—
U.S.—Alaskan Marine Shale	Small	Small	250	200	—	—
U.S.—other shales		Small	—	—	600	23,000
Canada	Small	Small	50	100	1000	23,000
South America	Small	800	—	3200	2000	36,000
Africa	100	Small	—	—	4000	80,000
Asia	90	14	2	3700	5400	110,000
Europe	70	6	100	200	1200	26,000
Australia and New Zealand	Small	1	—	—	1000	20,000
TOTALS GRAND TOTAL	678 92	2221 297	552 74	8800 1,179	15,200 2,037	318,000 Gbbl 42,600
% Rogner's RB	11%	34%	9%	1.4 x	2.3 x	53 x

0.134 t/bbl

Gto

(From U.S. Geological Survey Professic

RB = 870 Gto

Unconv #3: Technology

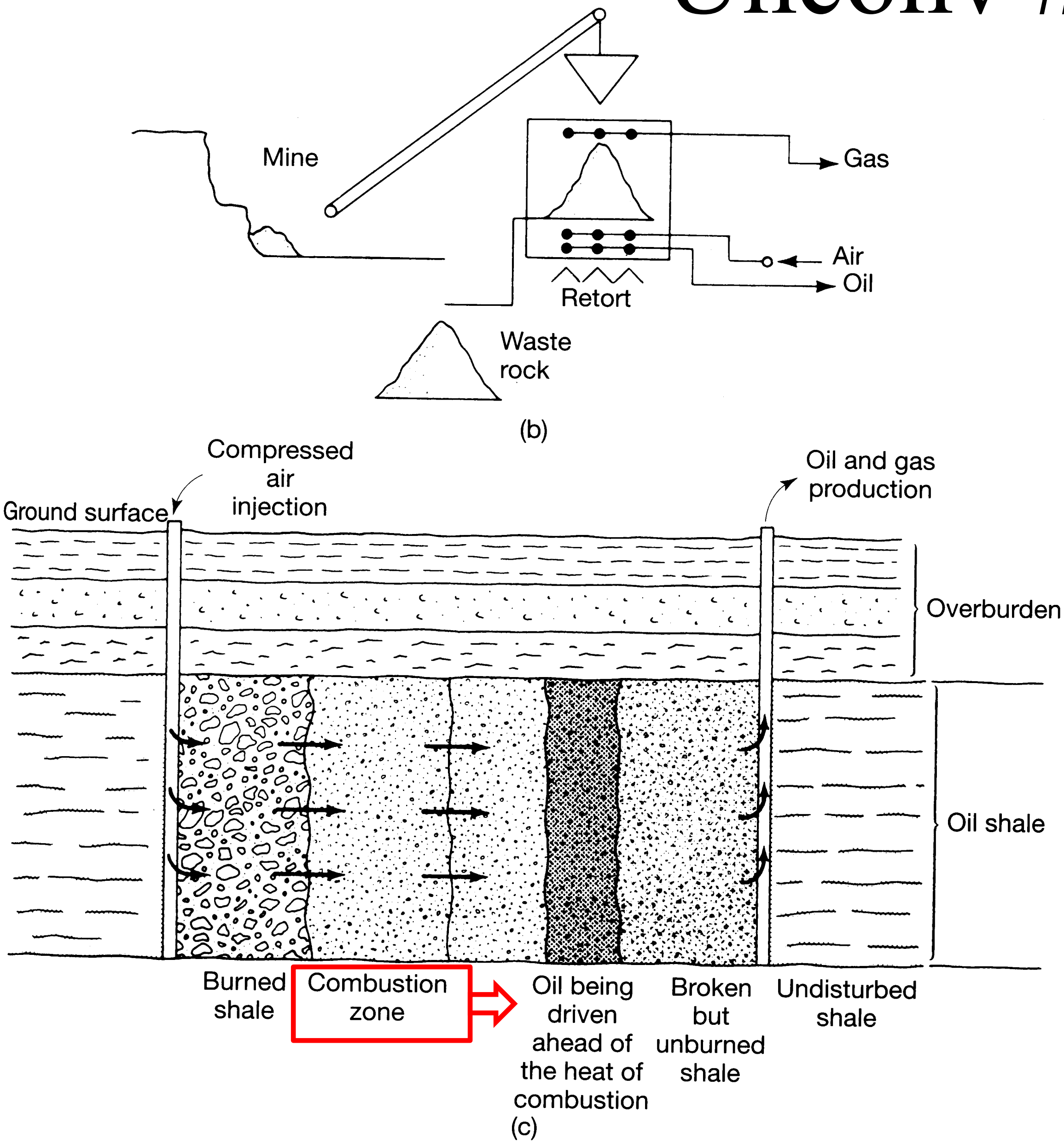
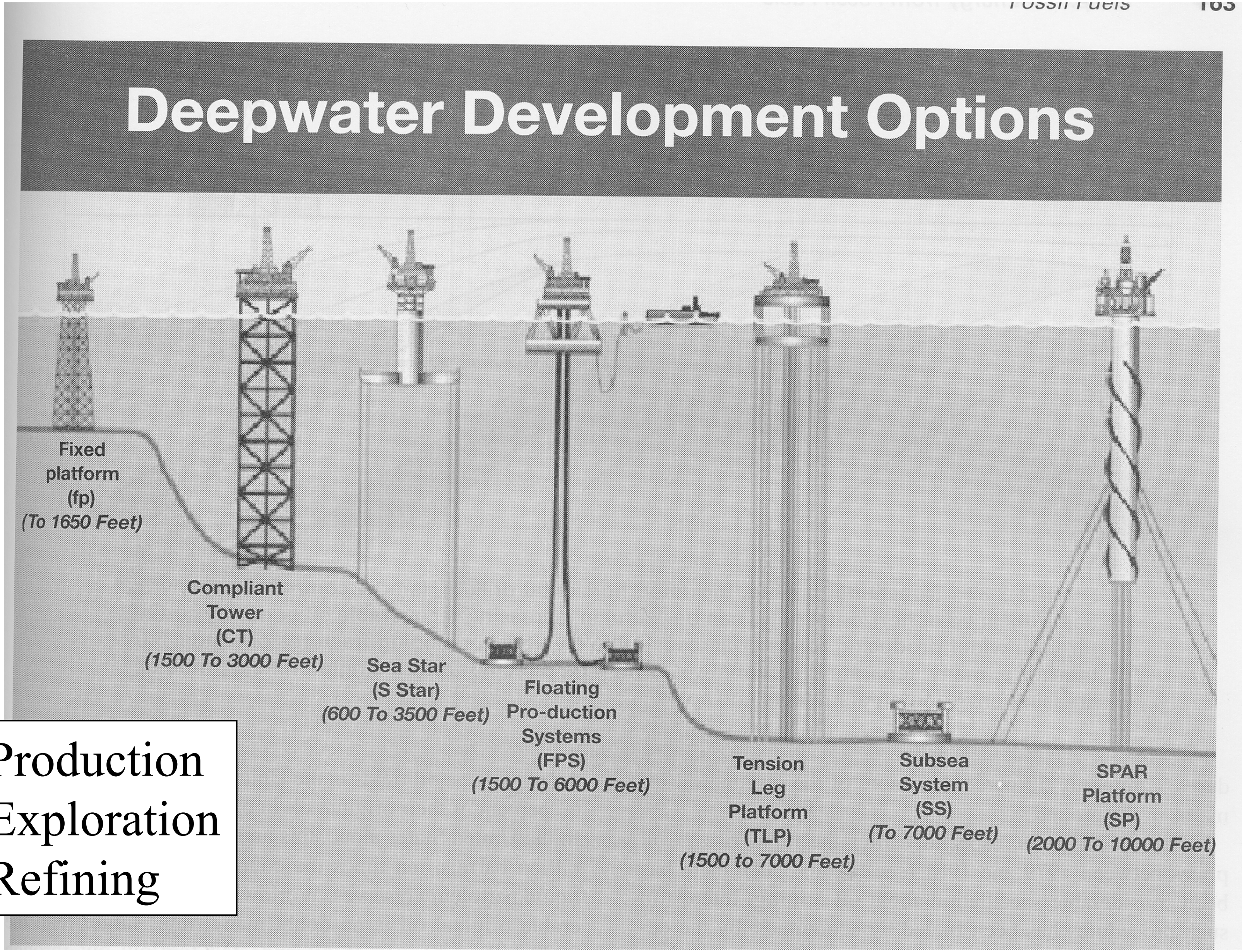


FIGURE 5.56 (a) A close-up view of a sample of rich oil shale. (b) Schematic diagram of the processing of oil shale after mining. The retort would be operated in 400° to 500°C to release the gas and oil from the crushed shale. (c) The in situ oil shale retorting process relies upon the movement of a combustion zone through the shale by injecting air into one well and extracting oil and gas from another well ahead of the combustion zone. The shale is first broken to permit the movement of air and gases.

Craig et al. (2001)

Technology:



- Production
- Exploration
- Refining

Craig et al. (2001)

Finding more:

“Oil is found in the mind…” Wallace Pratt

- Unexpected discoveries
  - Empty Quarter 200’ sand dunes
  - Paleozoic oil (even Cambrian in Oman; Mideast oil generally Mesozoic or Tertiary)
  - Barents Sea, Arctic,…
- Better exploration economics and recovery

  1980->2000
  - $/bbl discov $21->$6
  - Recovery 22% ->35%→50%

Natural Gas

Craig et al. (2001)

Convtional Reserves

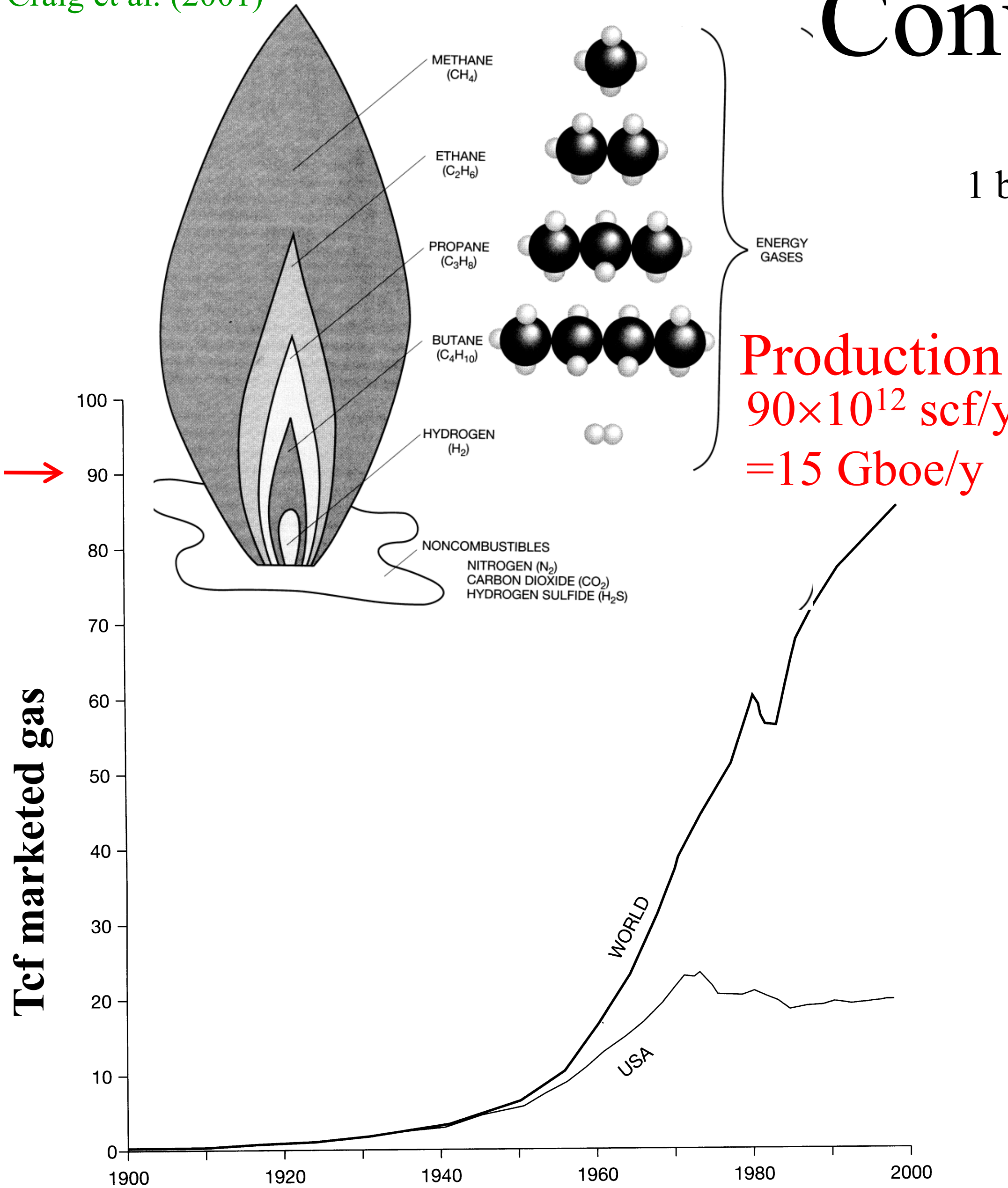


FIGURE 5.51 World production of natural gas has risen sharply since 1950 when pipelines and transport ships became available. Production in the United States peaked in the 1970s, but remains at nearly the same levels. (Data from the U.S. Energy Information Administration.)

TABLE 5.7
World natural gas reserves, 2000

1 bbloe = 6000 scf

		Reserves $ft^3 \times 10^{12}$	Reserves $m^3 \times 10^{12}$
North America			
United States	5.7%	164.0	4.65
Canada		63.9	1.81
Mexico		63.5	1.80
South America			
Venezuela	4.3%	142.5	4.04
Argentine		24.1	0.68
Others		52.5	1.49
Europe and Western Asia			
Russia		1700.1	48.18
Norway		41.4	1.17
Netherlands	42%	63.1	1.79
United Kingdom		27.0	0.77
Turkmenistan		101.0	2.86
Others		228.3	6.47
Middle East			
Iran	34%	812.3	23.02
Qatar		300.0	8.50
Saudi Arabia		204.5	5.79
United Arab Emirates		212.0	6.01
Iraq		109.8	3.11
Others		110.9	3.14
Africa			
Algeria	7%	130.3	3.69
Nigeria		124.0	3.51
Libya		46.4	1.31
Egypt		31.5	0.89
Others		28.9	0.82
Far East and Oceania			
Malaysia		81.7	2.32
Indonesia		72.3	2.05
China	7%	48.3	1.37
Australia		44.6	1.26
Others	5141/90 =	112.7	3.19
WORLD TOTAL	**57 yrs**	5141.6	145.69

1boe = 6000 SCF

Reserves (857 Gboe = 115 Gtoe)

14% Rogner's resource base of 814 Gtoe

USGS conv. gas resources

Reserves	867 Gboe
Reserve Growth	664
Undiscovered	1068

2600 Gboe 350 Gtoe

43% Rogner's resource base of 814 Gtoe

(but need to add historic production of 1 Tboe)

USGS Oil resource (2311 Gbo, 309 Gto)

43% Rogner's resource base of 870 Gto

(on same basis)

U.S. Geological Survey world petroleum assessment 2000,
http://pubs.usgs.gov/dds/dds-060/ESpt6.hml

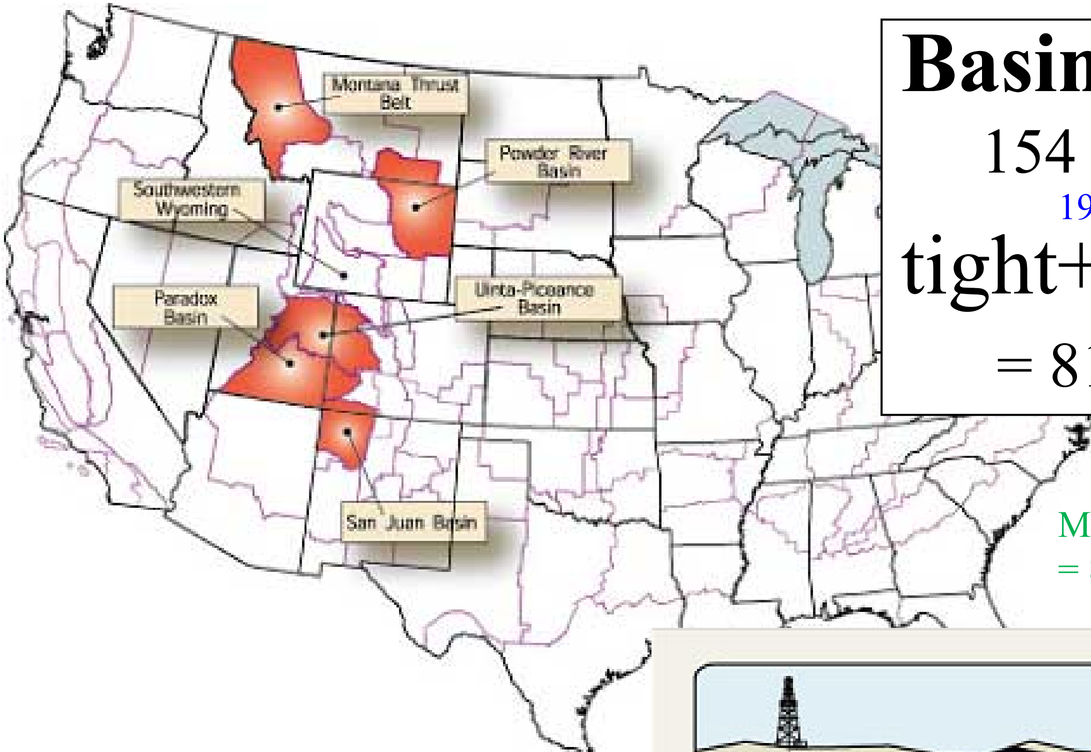
Basin Center Gas

154 Gtoe in 4 basins (resource)

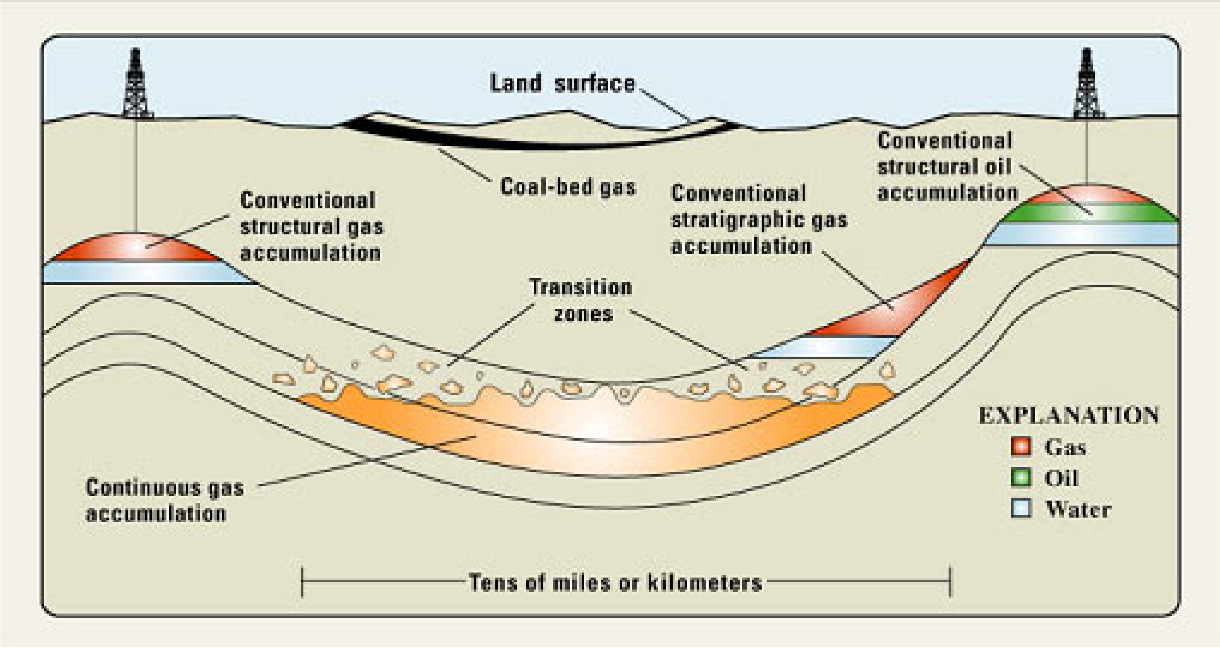
19% Rogner's RB_{814}

tight+shale+coal gas

= 818 Gtoe 100% Rogner's RB_{814}



Marcellus = (363 tcf /6000 tcf/boe))x0.134 toe/boe = 8 Gtoe



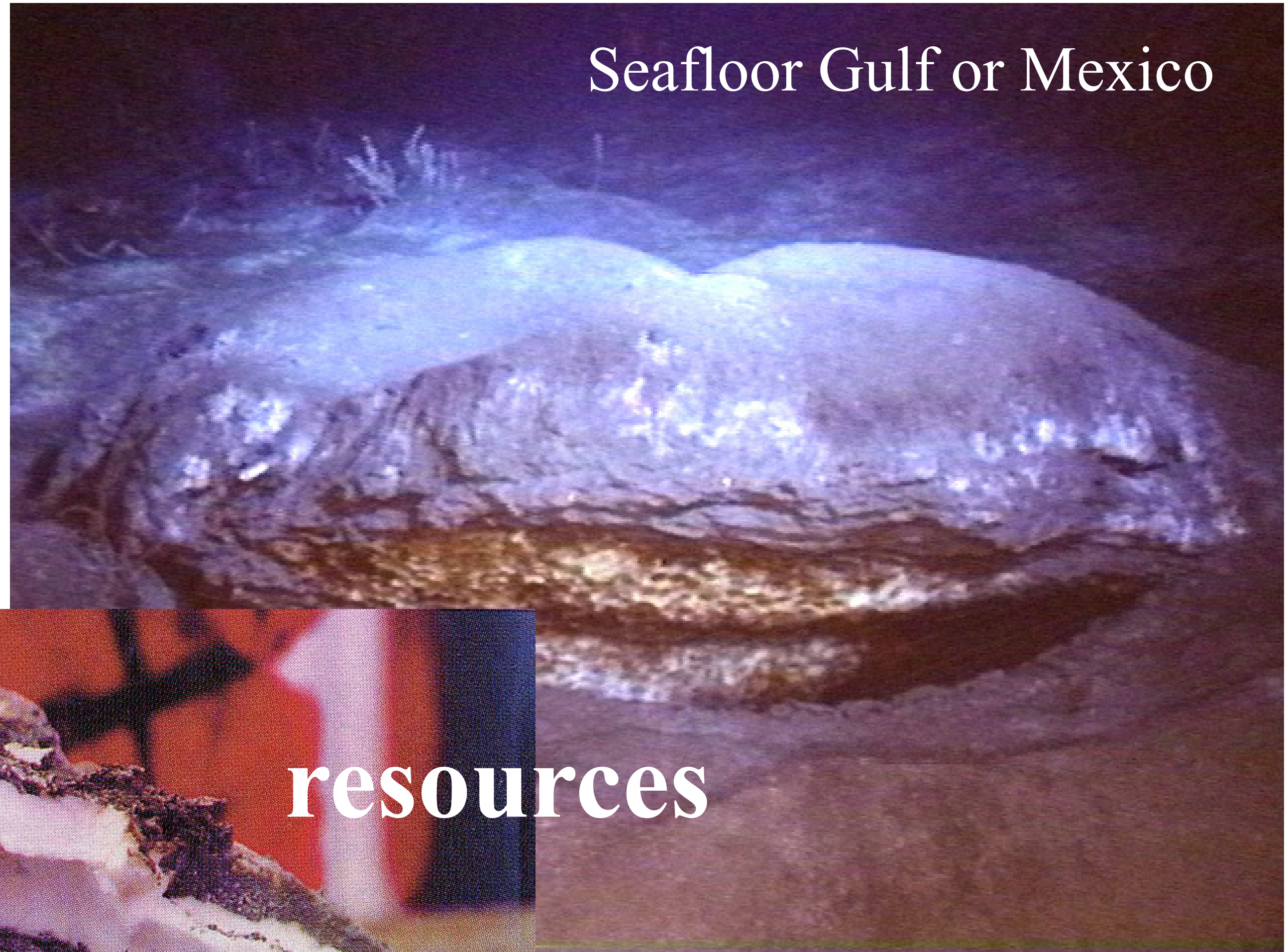
Basin center gas plus
Tight+shale+coal=
119% of Rogner's RB_{814}
(not counting historic production)

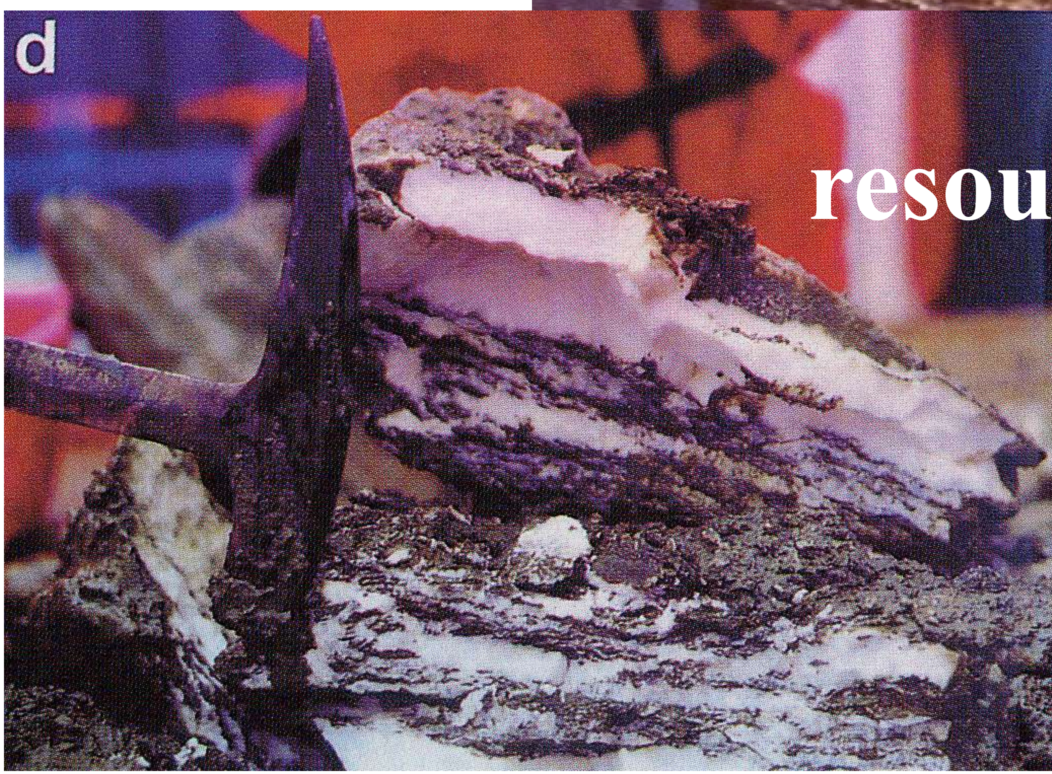
http://www.kkrva.se/images/energi/odell

Methane Hydrate

the ice that burns

Seafloor Gulf or Mexico





resources

$3xRB_{814}$

US 95% Confid 2500 Gtoe

50% Confid 7100 " $9xRB_{814}$

World est. to 1,165,000 "

$1431=RB_{814}$

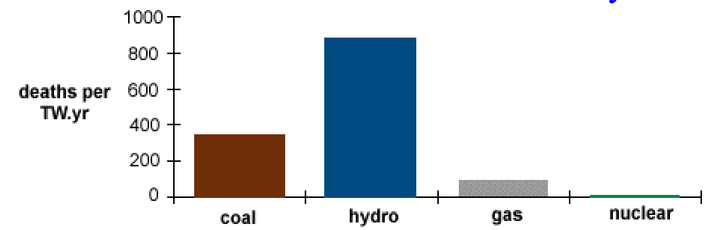
USGS Fact Sheet FS-021-01

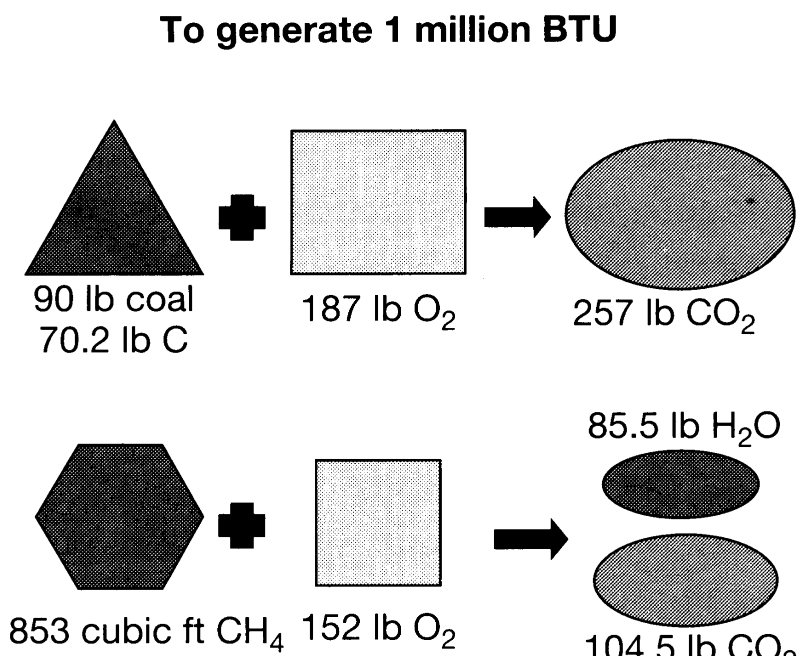
Coal

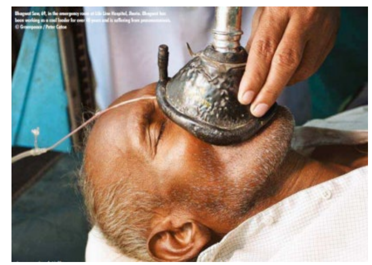
… the least desirable (but most abundant) fossil fuel

Coal is hazardous and produces more CO_2

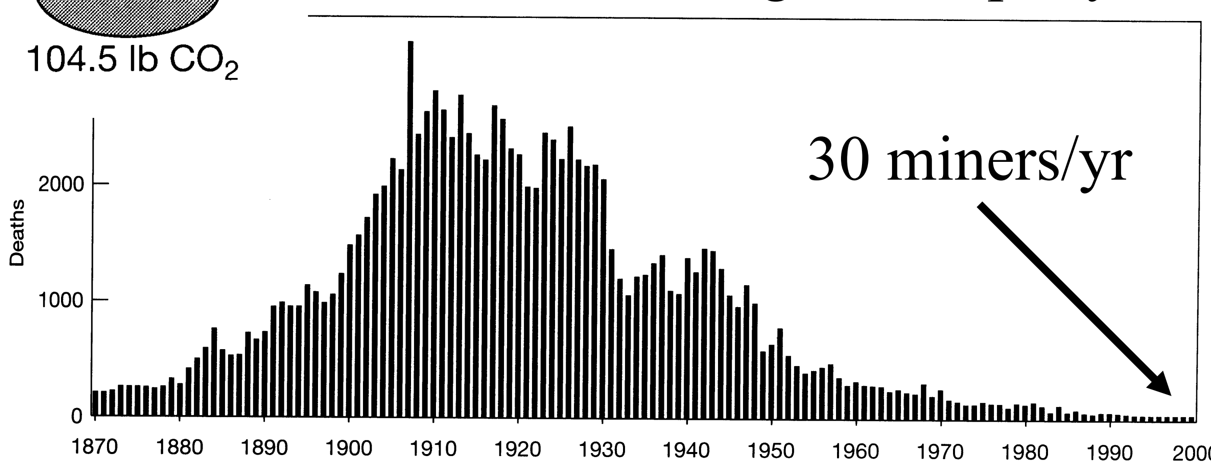
…but not as hazardous as hydro





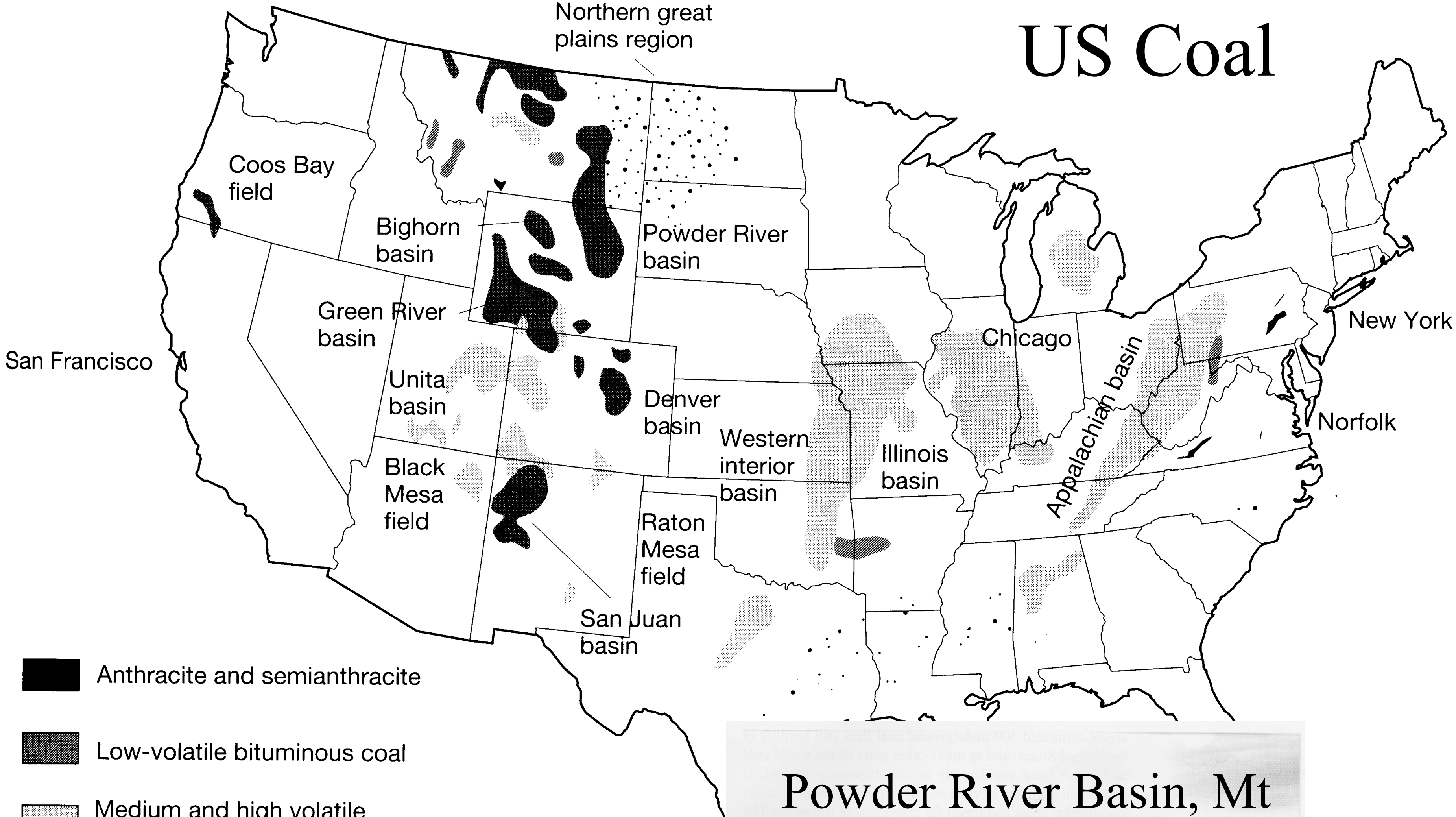


US Coal mining deaths per year



Craig et al. (2001)

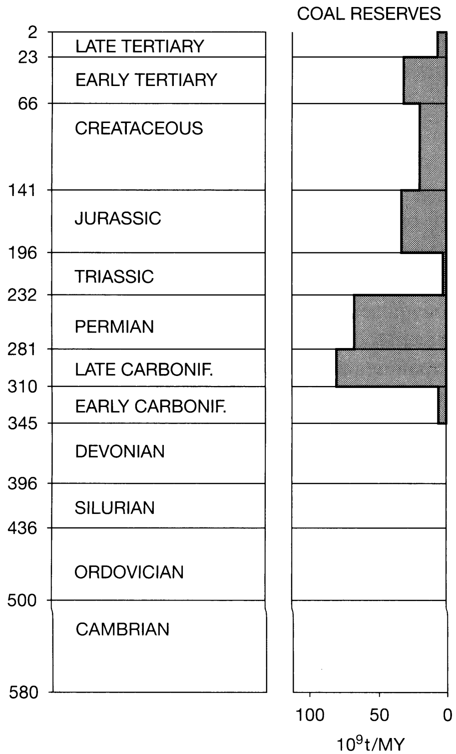
US Coal



Powder River Basin, Mt

Craig et al. (2001)

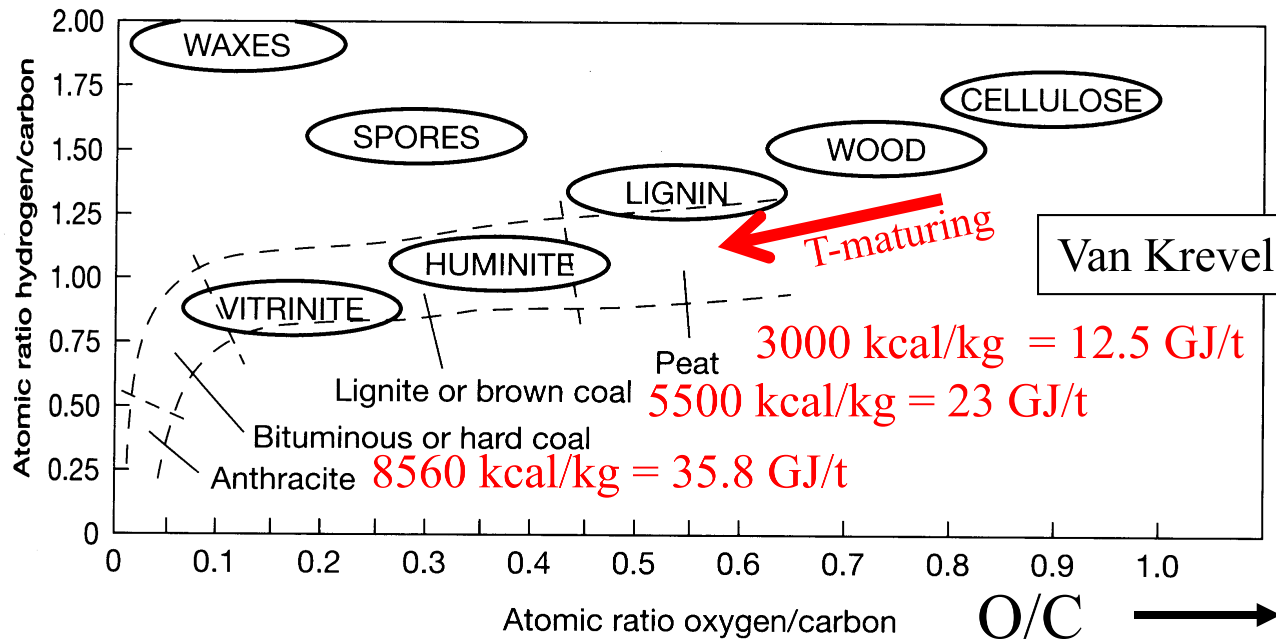
COAL



Glacial

- Deposition today in Dismal Swamp of Virginia and NC, coastal swamps of Canada, Scandanavia, Ireland
- Peat forming today and can be reharvested in many areas every 5 to 10 years
- Ireland gets 25% energy from peat
- Peat matures to coal by loosing O and H and concentrating C:

H/C



Van Krevelen Diagram

O/C

Craig et al. (2001)

Coal largest conventional FF resource

	Reserves*		Resources**		
Fuel	*Conventional Units*	*Joules* (× 10^{19})	*Conventional Units*	*kw hr* (× 10^{12})	**Joules** **(×** $\mathbf{10^{19}}$**)**
Peat	50 × 10^9 tons	97	* 240 × 10^9 tons	1289	* 464
Coal	986.54 × 10^9 tons	2344	7800 × 10^9 tons	51,480	18,533
	664 Gtoe of coal		5257 Gtoe of coal		
	19% RB_{3400}		1.5 RB_{3400}		

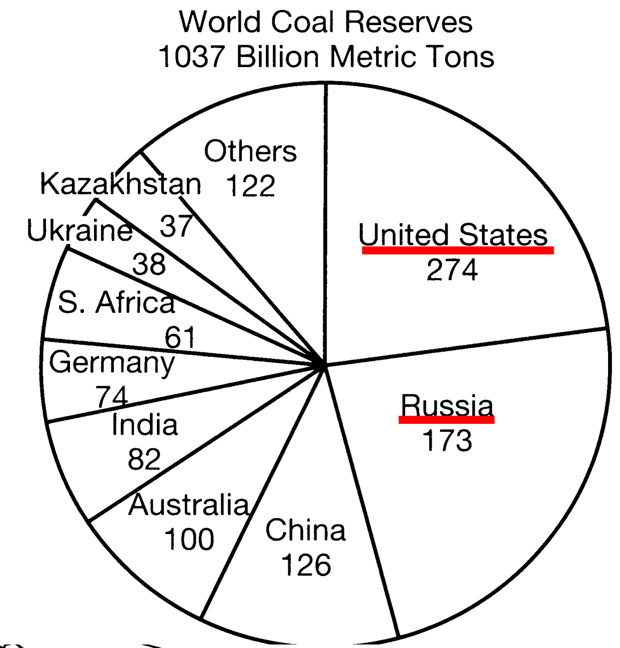
Rogner's Resource Base coal = 5041 Gt coal
= 3400 Gtoe

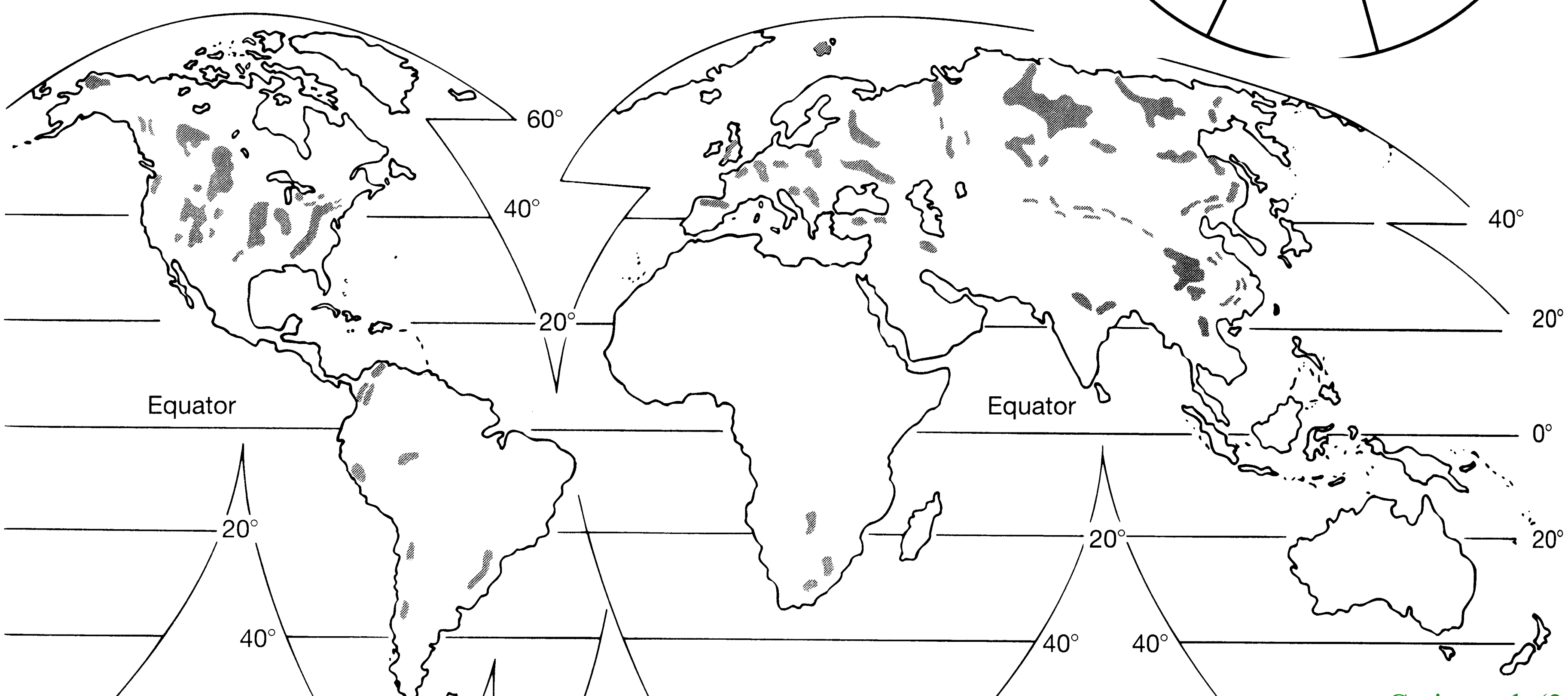
Rogner's Resource Base oil = 814 Gto

4.2 x more coal than oil

Craig et al. (2001)

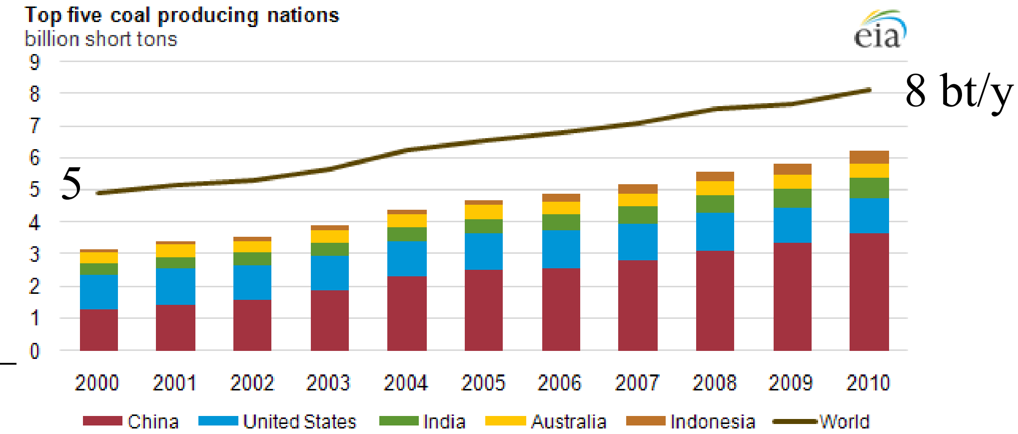
Coal Giants
US, Russia, China

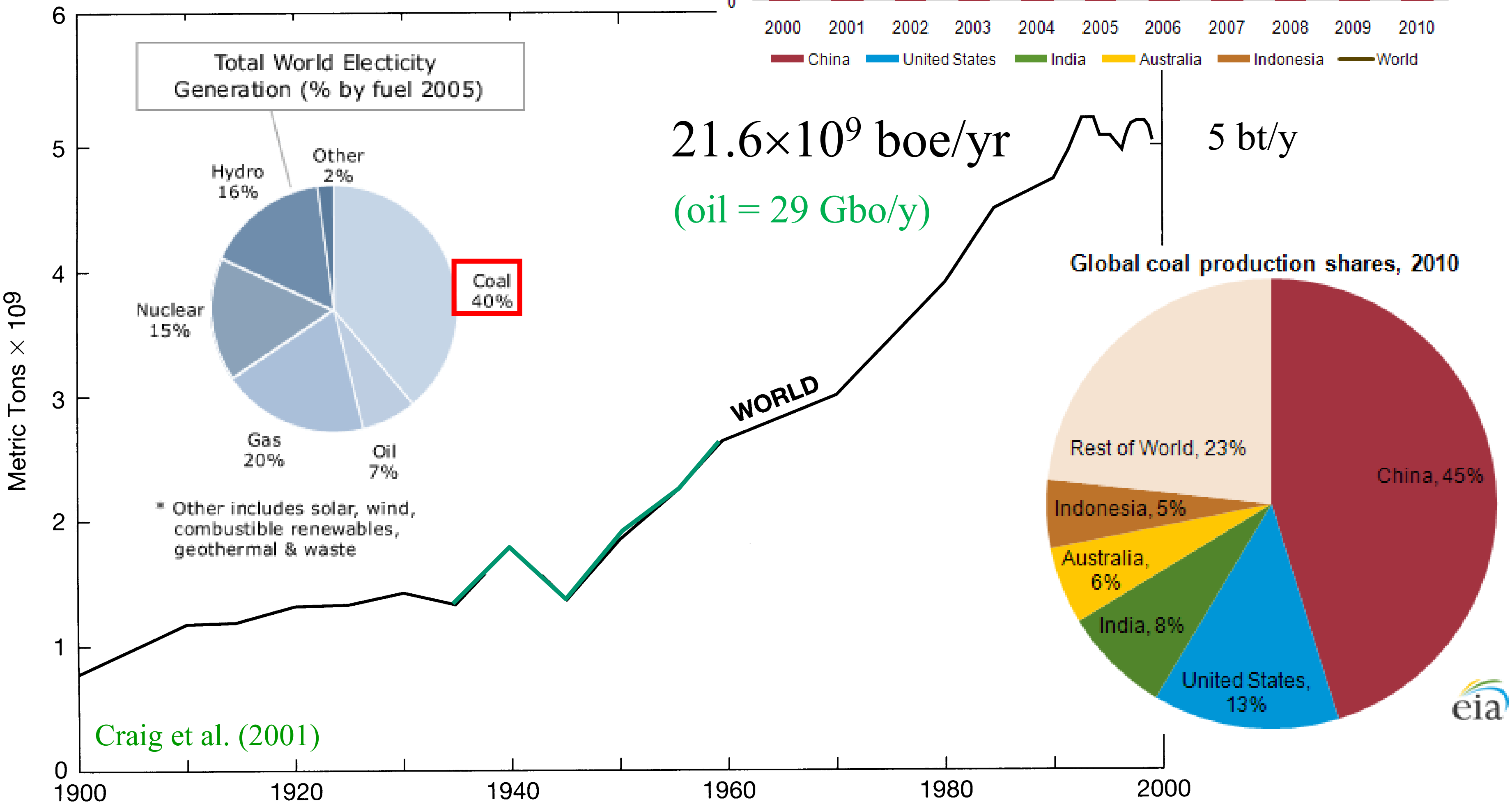




Craig et al. (2001)

Coal production is rising



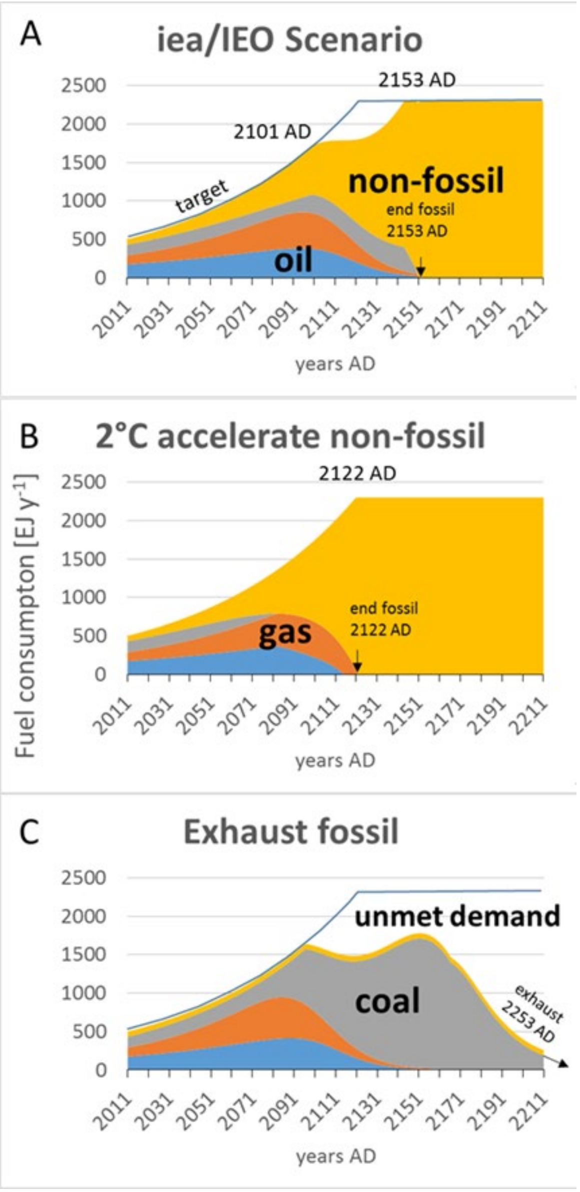


Insert: http://www.worldcoal.org/pages/content/index.asp?PageID=188

Summary

	USGS Resources Gtoe (Gboe) [%RB]	Unconventional %RB ID Hyp Spec	Rogner Resource Base (Gtoe)	GtC/ PAL
Gas	350 (2600)[43%]	Basn Ctr: 14% RB_{814} shale+coal gas: 119% RB_{814} Hydrate: 1431 RB_{814}	814	0.9
Oil	309 (2311)[36%]	Tar sands: 106% RB_{870} Oil shale: 1.4 55 RB_{870}	870	1.2
Coal	5921 (44,000)[117%]		3400	6.6
		TOTAL	5084	8.8

Scenarios



Straight IEO projection

$a_{non-FF} = 0$

99.3% oil

97.7% gas consumed = 3.4 PAL

19.1% coal

$\Delta_{pre-ind} T=2.7°C$

% Rogner's RB

Meet Paris Accord

$a_{non-FF} = 0.22\%/y$

74.3% oil

87.6% gas consumed = 2.1 PAL

6.3% coal

$\Delta_{pre-ind} T=2°C$

Worst Case (exhaust resource base)

$a_{non-FF} = 0$

$G_{non-FF} = 0$

100% oil

100% gas consumed = 8.8 PAL

100% coal

$\Delta_{pre-ind} T=4.4°C$

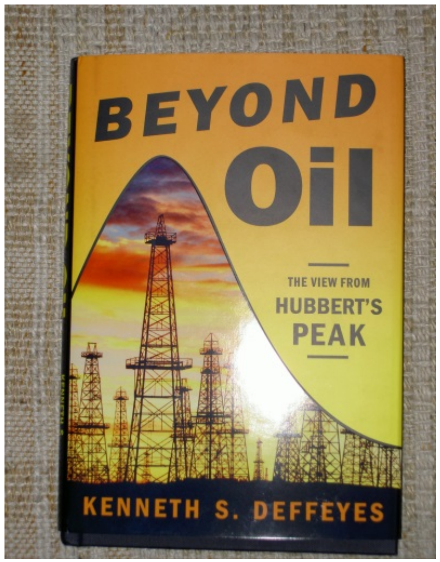
Prosperity goal cannot be met without non-fossil fuels

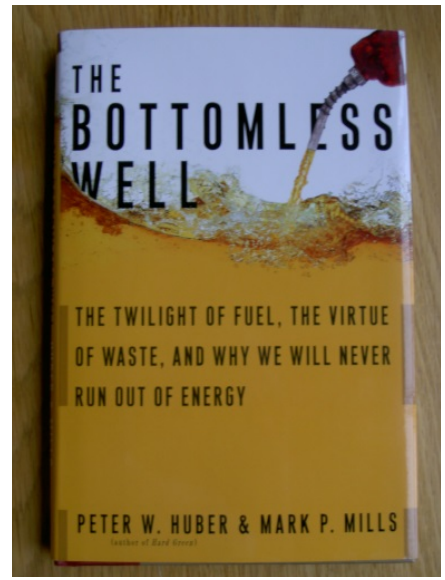
Conclusions

1. End of fuel age probably exaggerated

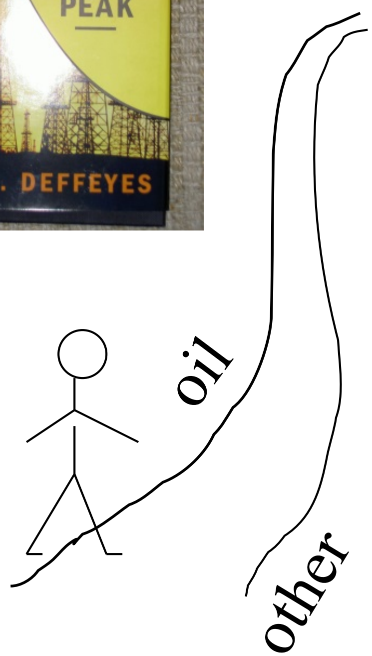
Transition

1. Worrisome
2. Exciting





"Brook is wide.
Will be tough to cross.
Better start to appreciate that crossing will put our civilization to a severe test."



"Crossing brooks is what we do.
Always better on the other side.
Progress and change is the human imperative."

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