The origin and evolution of life on Earth

The tree of life

- How did life begin on Earth?
- Miller-Urey.
- RNA world.
- The first cell - the single common ancestor.
- Life's basic code: 20 amino acids, DNA heredity, ATP-based cell energy.
- The age of bacteria/archea. The rise of eukaryea.
- Where did this occur? Hydrothermal vents?
- A short history of life from day one: the rise of oxygen, the Cambrian explosion, the K-T impact.

How did life originate on Earth?

- All life today on Earth is descended from other life
- We do not see any cases of life arising spontaneously
  - all modern-day cells contain DNA, which is too sophisticated for life to have originated recently
- However, the early Earth would have been more suitable for the spontaneous emergence of life
  - lots of organic material
  - little oxygen in the atmosphere
  - less competitive environment

The Miller-Urey experiment

- Urey proposed that reactions in the atmosphere of the early Earth would produce simple organic chemicals, e.g. methane, ammonia, water, hydrogen sulphide.
- Miller then demonstrated that combining a gaseous mixture of the above chemicals in a spark chamber would create 22 types amino acids - some of the simplest building blocks of life.
- The Urey component of the experiment is still debated, i.e. did the simple organics form in the atmosphere or via volcanic outgassing. How long did the hydrogen last?
- However, the Miller component has been extended to demonstrate the creation of nucleotides and other components of life.

The Urey atmosphere

$$C + 2H_2 \rightarrow CH_4$$

$$N_2 + 3H_2 \rightarrow NH_3$$

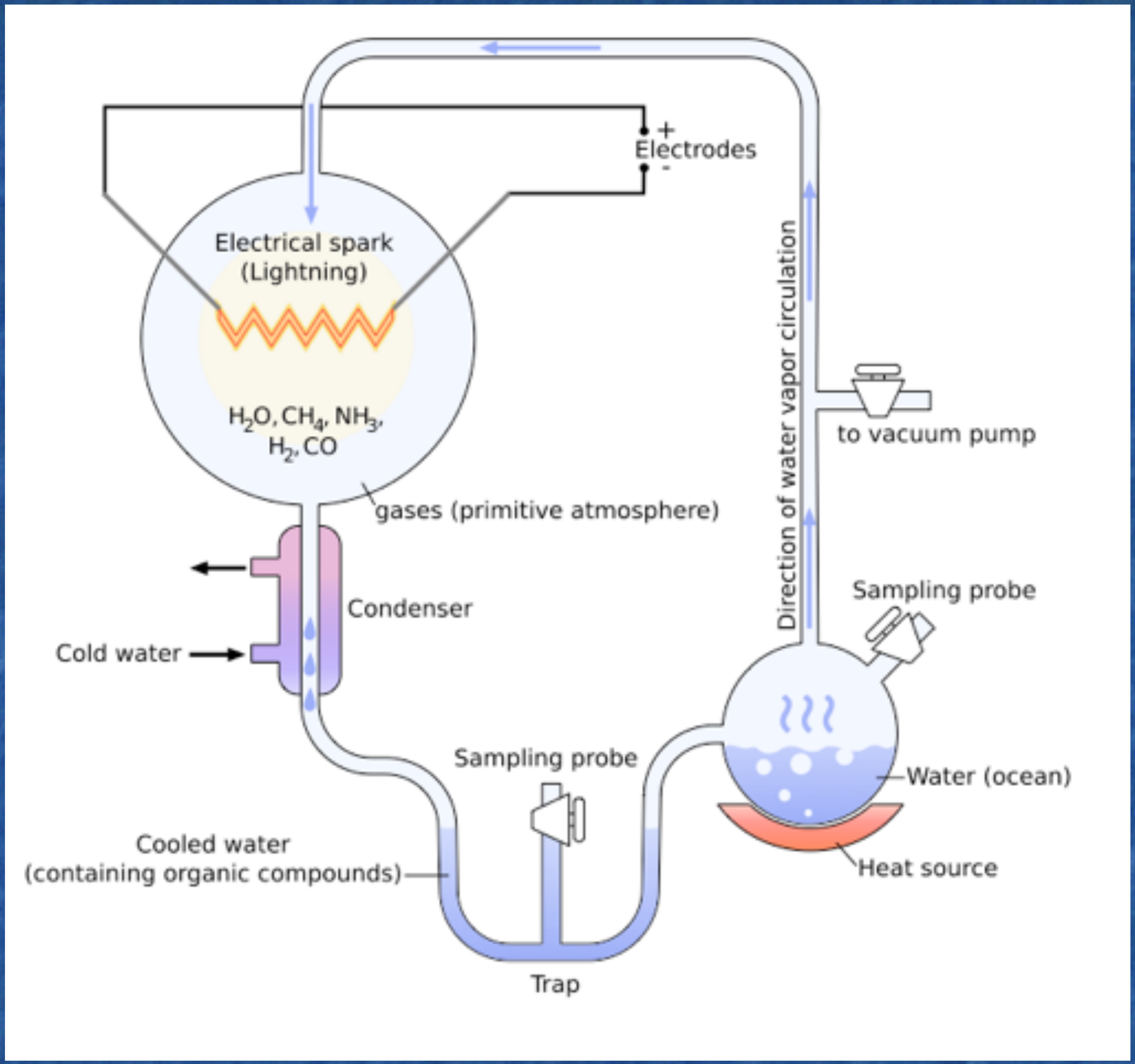
$$O_2 + 2H_2 \rightarrow H_2O$$

$$S + H_2 \rightarrow H_2S$$

$$CO_2 + 6H_2 \rightarrow CH_4 + 2H_2O$$

Urey, H. C. (1952) On the early chemical history of the Earth and the origin of life. *Proc. Natl Acad. Sci. USA* 38: 351-363

Stanley Miller, University of Chicago, 1953



$CO_2 \rightarrow CO + [O]$ (atomic oxygen)

$CH_4 + 2[O] \rightarrow CH_2O + H_2O$

$CO + NH_3 \rightarrow HCN + H_2O$

$CH_4 + NH_3 \rightarrow HCN + 3H_2$

These compounds then react with the formation of aminoacids (Strecker synthesis) and other biomolecules:

$CH_2O + HCN + NH_3 \rightarrow NH_2\text{-}CH_2\text{-}CN + H_2O$

$NH_2\text{-}CH_2\text{-}CN + 2H_2O \rightarrow NH_3 + NH_2\text{-}CH_2\text{-}COOH$ (glycine)

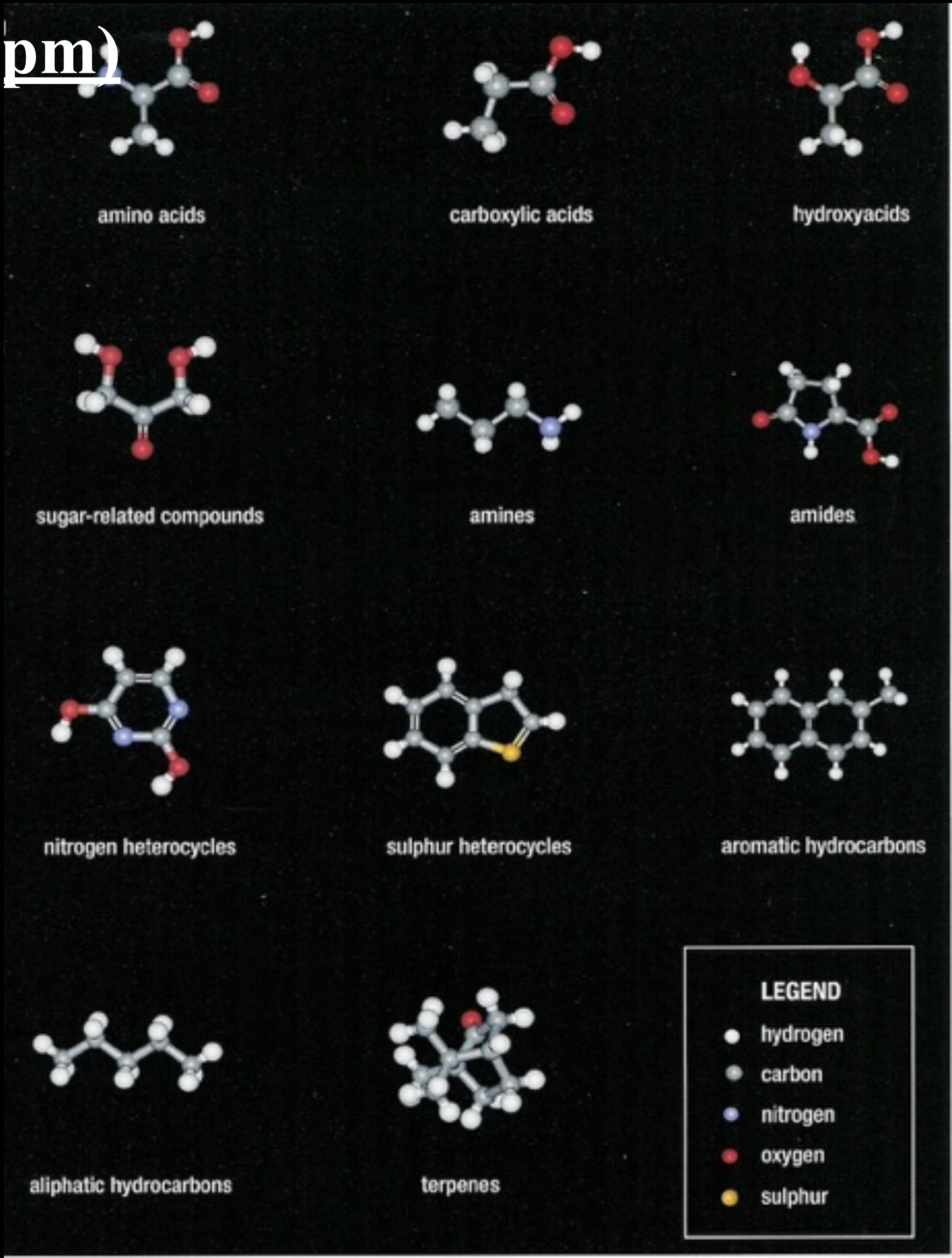
Miller-Urey today

Could life have migrated to Earth after originating elsewhere?

- If life originated elsewhere in the Solar System, could it have migrated to Earth on a meteorite or comet and seeded life on Earth?
- This idea is know as panspermia.
- Challenges would include surviving the impact, potentially millions of years in space, and the fiery descent to Earth.
- Organic compounds such as amino acids have been discovered within meteorites, e.g. Murchison.
- Could this new life survive and grow on Earth?
- Could life from Earth have seeded life elsewhere in the Solar System?

Abundances of soluble organic compounds in the Murchison meteorite (Botta & Bada 2002, Sephton 2002, 2004)

Compound Class		Concentration(ppm)
Amino Acids	CM	17-60
	CI	~5
Aliphatic hydrocarbons		>35
Aromatic hydrocarbons		3.3
Fullerenes		> 1
Carboxylic acids		> 300
Hydroxycarboxylic acids		15
Dicarboxylic acids & Hydroxydicarboxylic acids		14
Purines & Pyrimidines		1.3
Basic N-heterocycles		7
Amines		8
Amides	linear	> 70
	cyclic	> 2
Alcohols		11
Aldehydes & Ketones		27
Sulphonic acids		68
Phosphonic acids		2



Martian microbes in ancient meteorite?

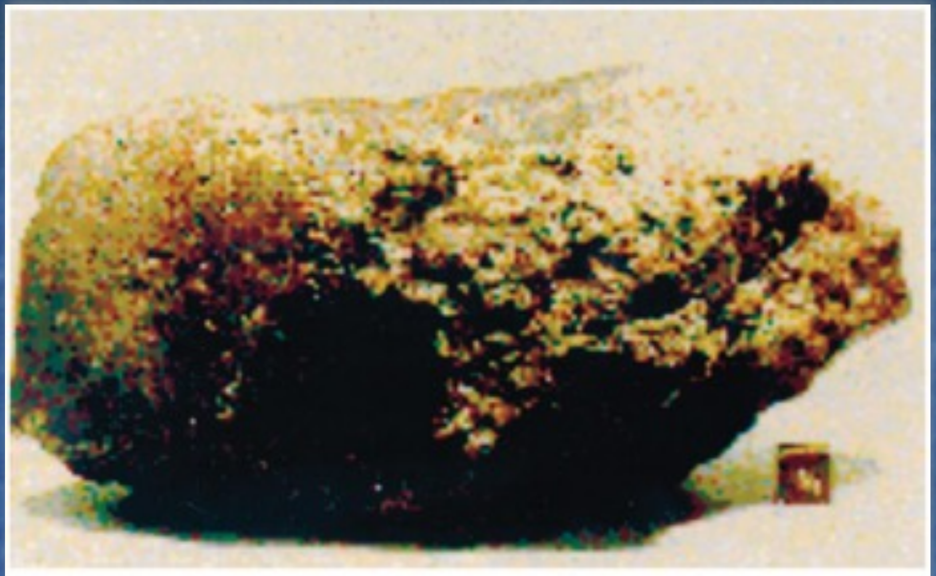
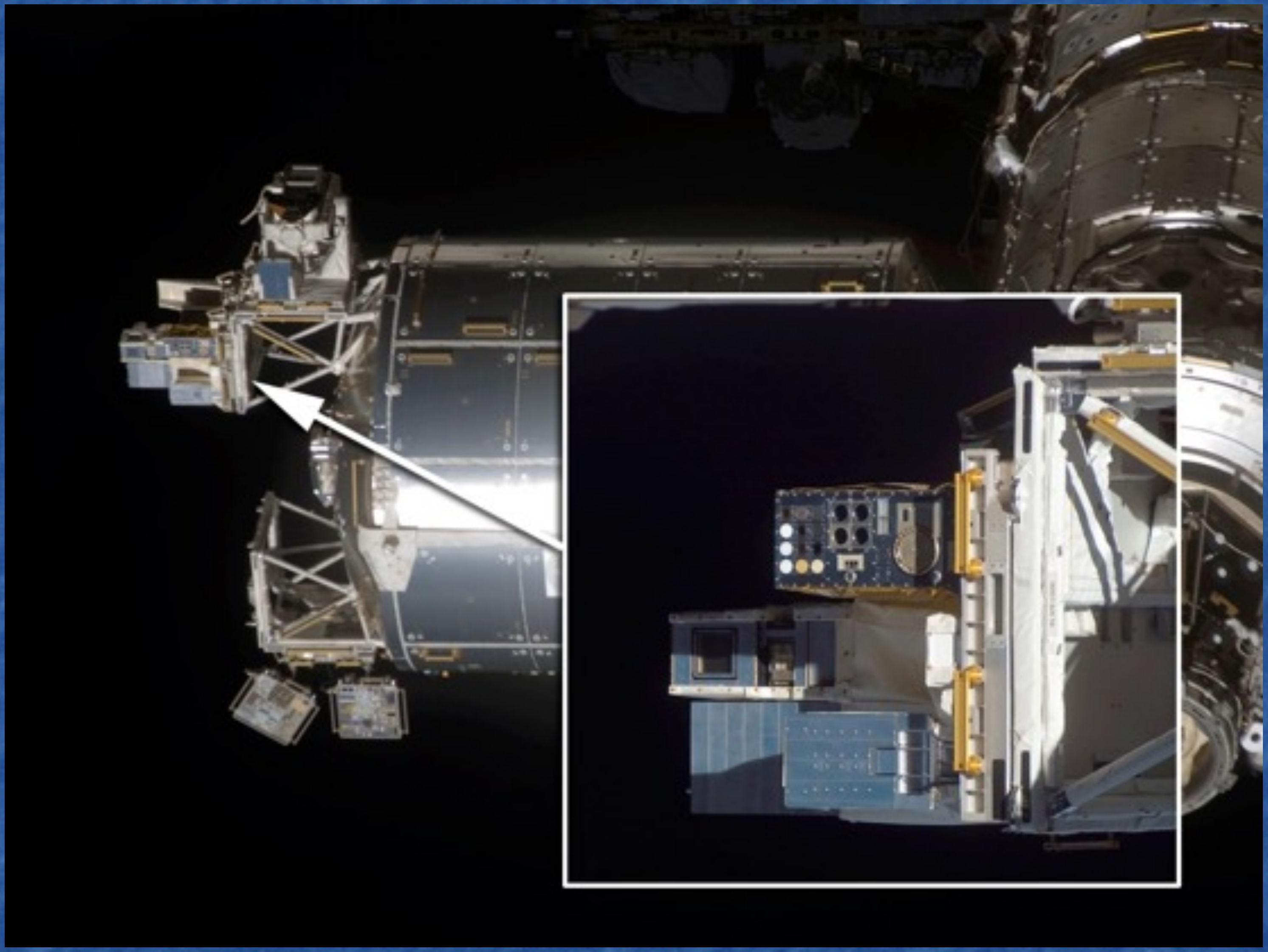


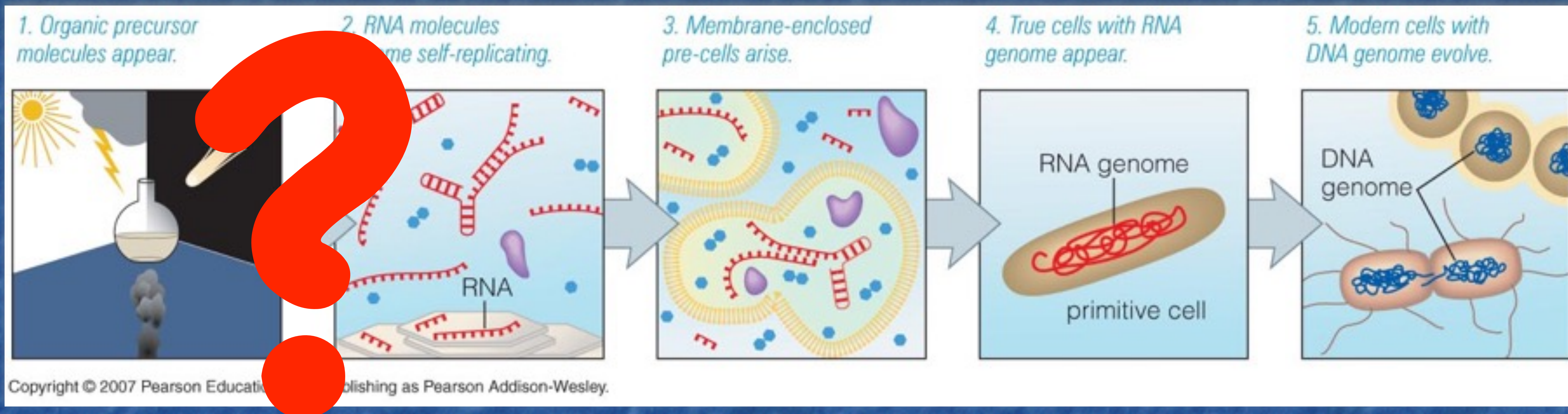
TABLE 8.3 *The History of Meteorite ALH84001*

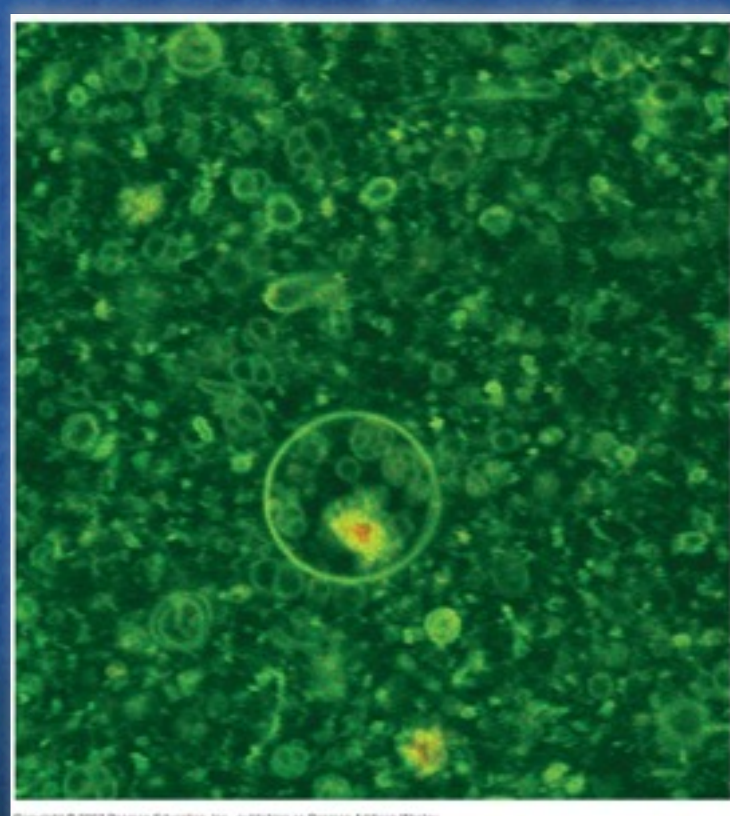
Time	*Event*
4.5 billion years ago	Solidifies from molten rock in the southern highlands of Mars
4.0–4.5 billion years ago	Affected by nearby impacts, but not launched into space
3.9 billion years ago	Infiltrated by water, leading to the formation of carbonate grains within the rock
16 million years ago	Blasted into space by an impact on Mars
13,000 years ago	Falls to Earth in Antarctica
December 27, 1984	Found by scientists
October 1993	Recognized as a martian meteorite
August 1996	Announcement that ALH84001 contains possible evidence of martian life



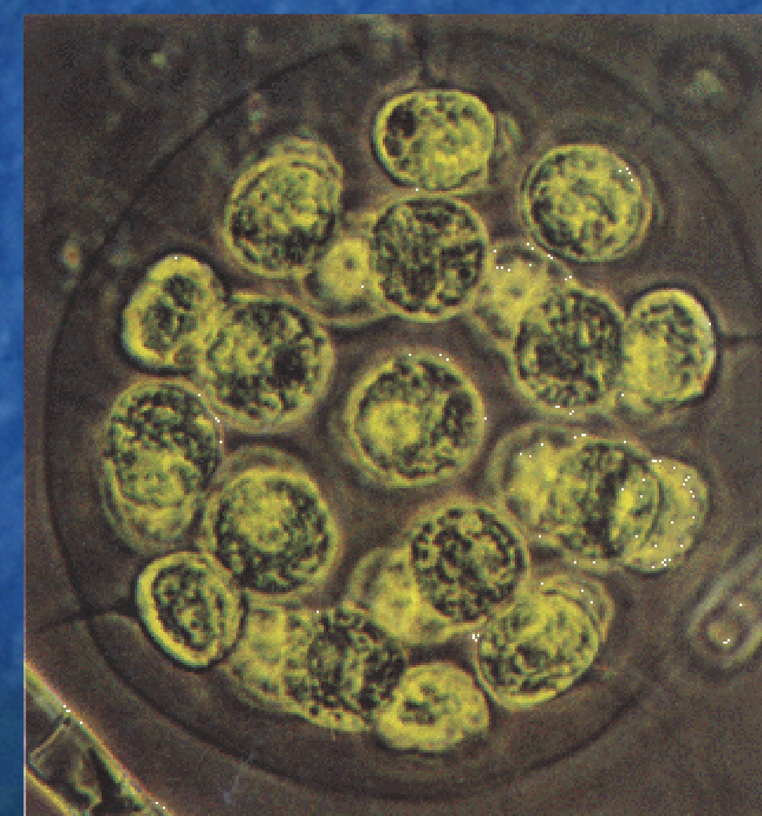
Beer in space?

The chemistry of early life





Pre-cell (not living)



Cells (living)

The RNA world

- "At some point a particularly remarkable molecule was formed by accident. We will call it the Replicator. It may not have been the biggest or the most complex molecule around, but it had the extraordinary property of being able to create copies of itself."

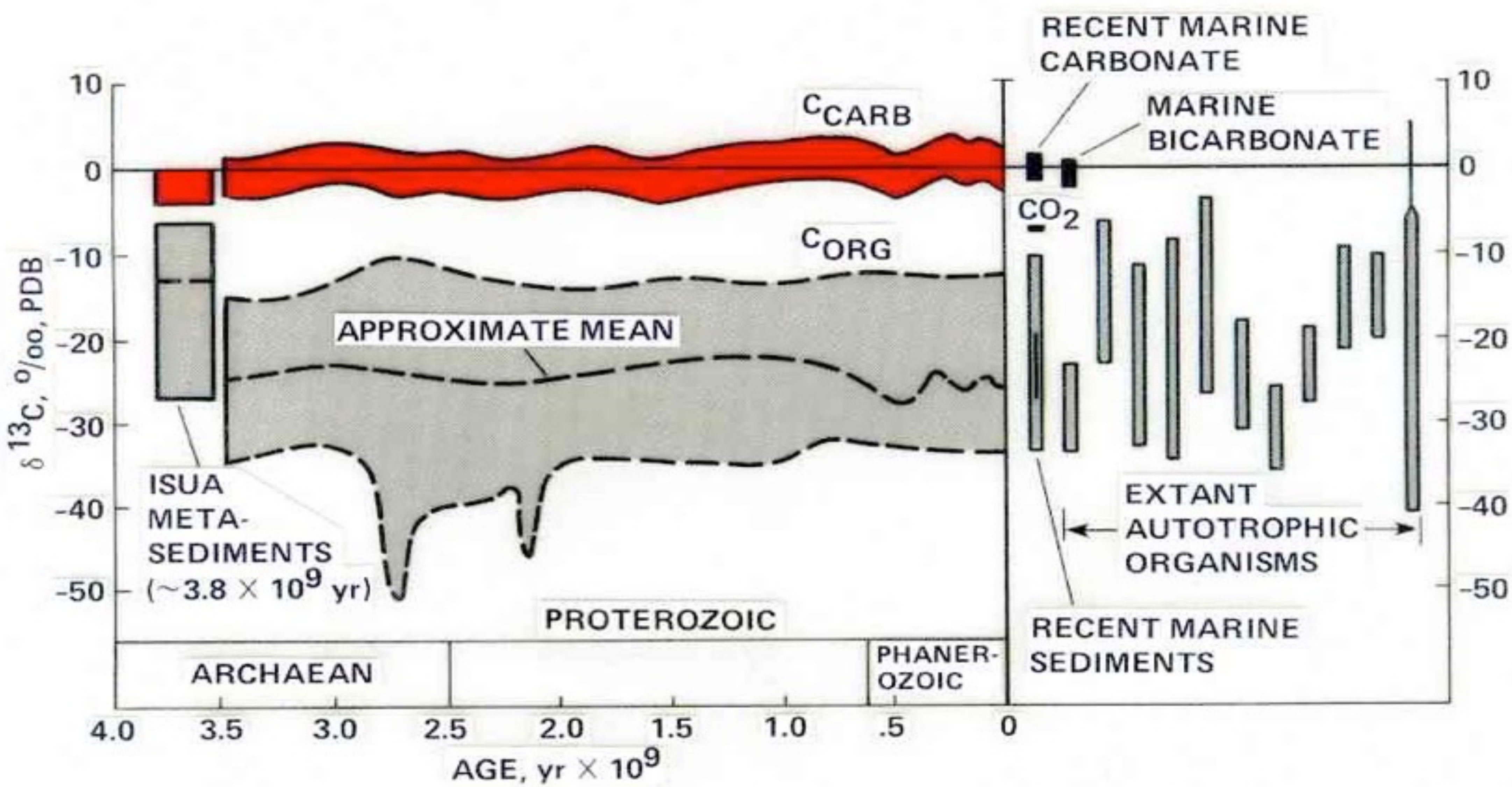
  Richard Dawkins
- RNA is still a complex molecule. Could such a molecule arise by chance? Could increasingly complex cycles of organic chemical reactions (perhaps facilitated by mineral clay surfaces) build the pre-cursor of RNA?
- Faster, more accurate replicators evolve quickly and begin to dominate.

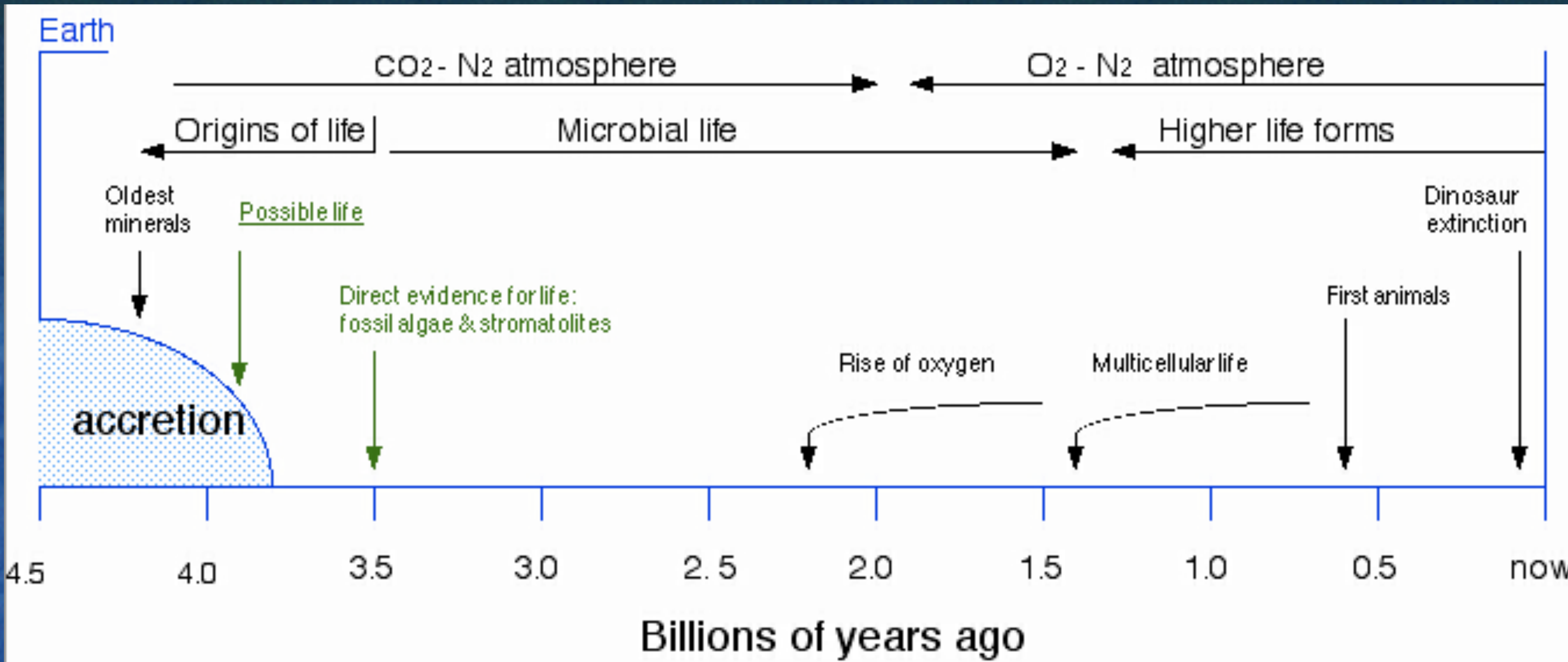
A Brief History of Life on Earth

- Primitive anaerobic microbial life forms
  - anaerobic life doesn't need molecular oxygen to survive
- Rapid evolution and diversification due to high mutation rate in DNA copying
  - fewer enzymes would have meant more DNA copying errors
- Photosynthesis and cyanobacteria => buildup of oxygen
  - extinction of many anaerobic microbes, rise of aerobic life forms
  - production of ozone, the land becomes habitable
- Rise of multi-cellular organisms (about 1.2 Gyr ago)
- The Cambrian Explosion (545 Myr ago)
- Colonization of land (475 Myr ago)

Continuity of life on Earth over 3.8 Gyr

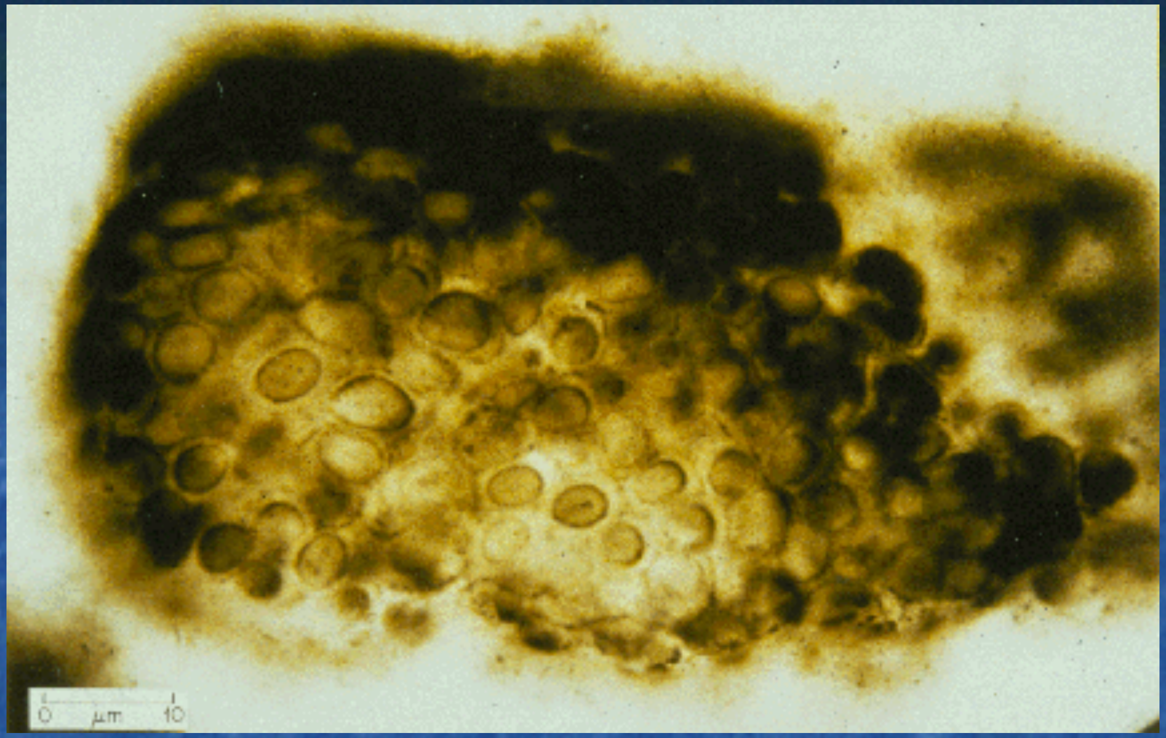
- ^{13}C isotope record back to 3.8 Gyr





a These large mats at Shark Bay, Western Australia, are colonies of microbes known as "living stromatolites"; they stand about knee-high. Microbes near the top generate energy through photosynthesis.

b The bands visible in this section mat are formed by layers of sedin different types of microbes.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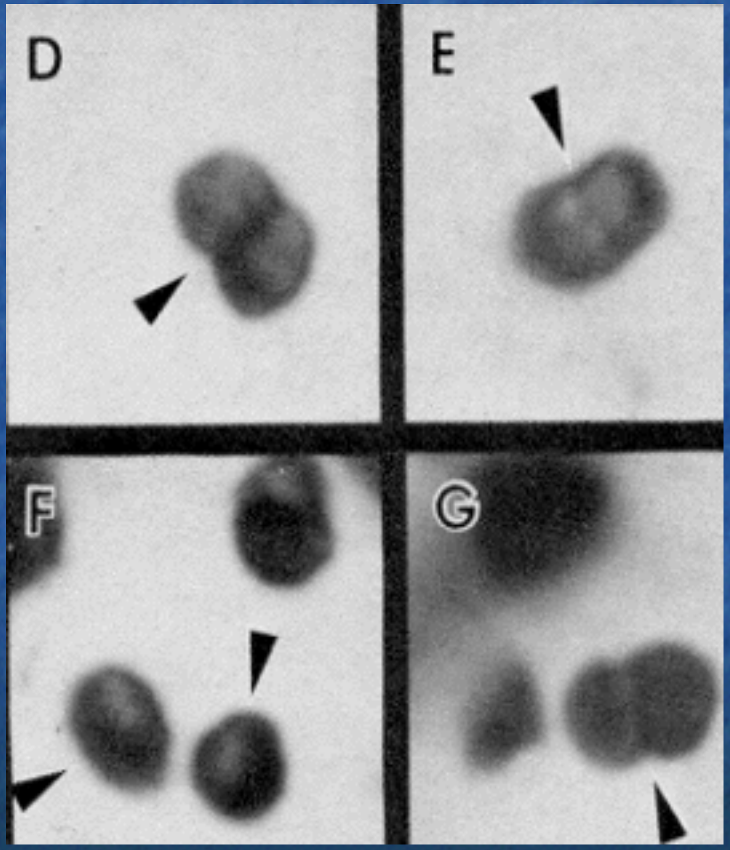
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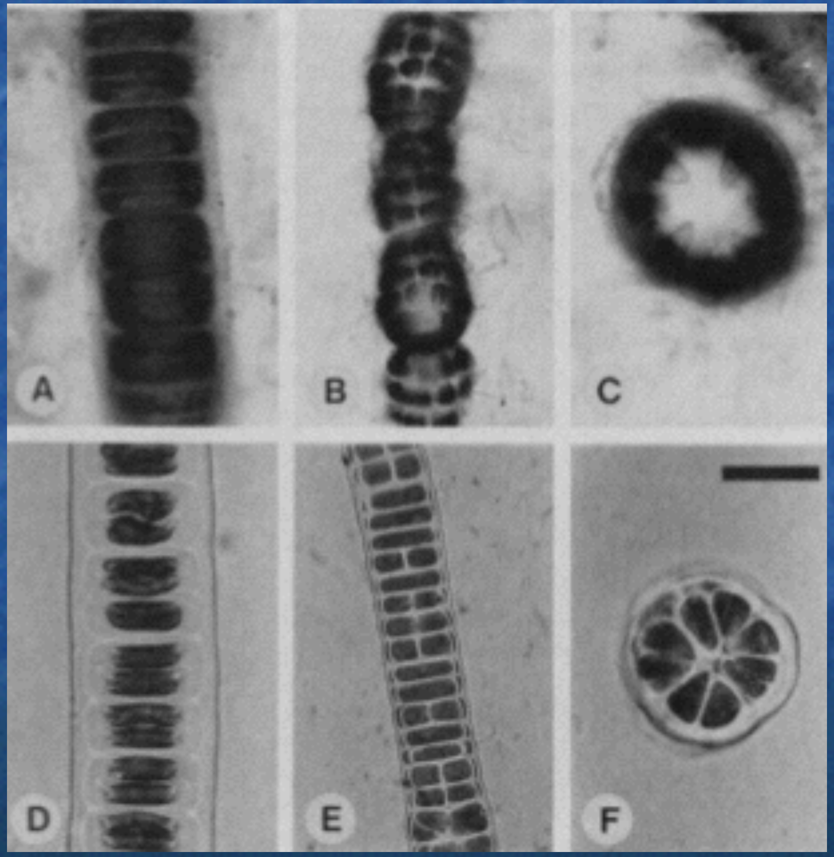
A
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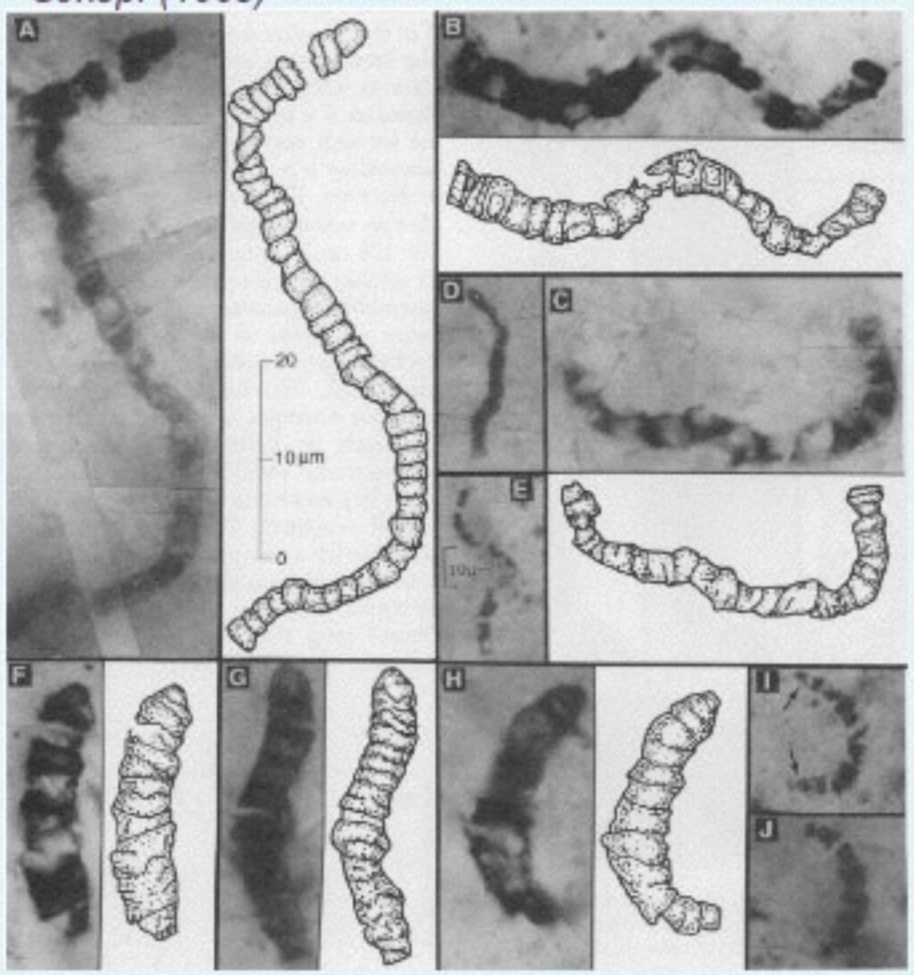
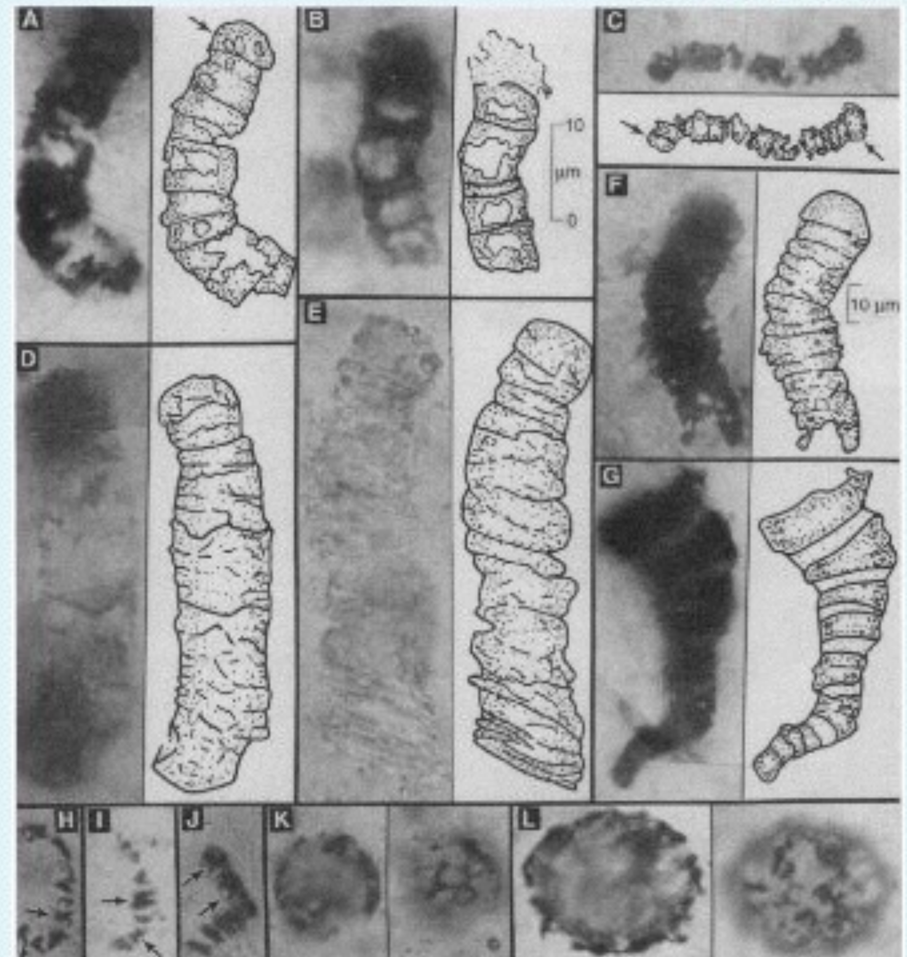
The Apex Chert

Schopf (1993)



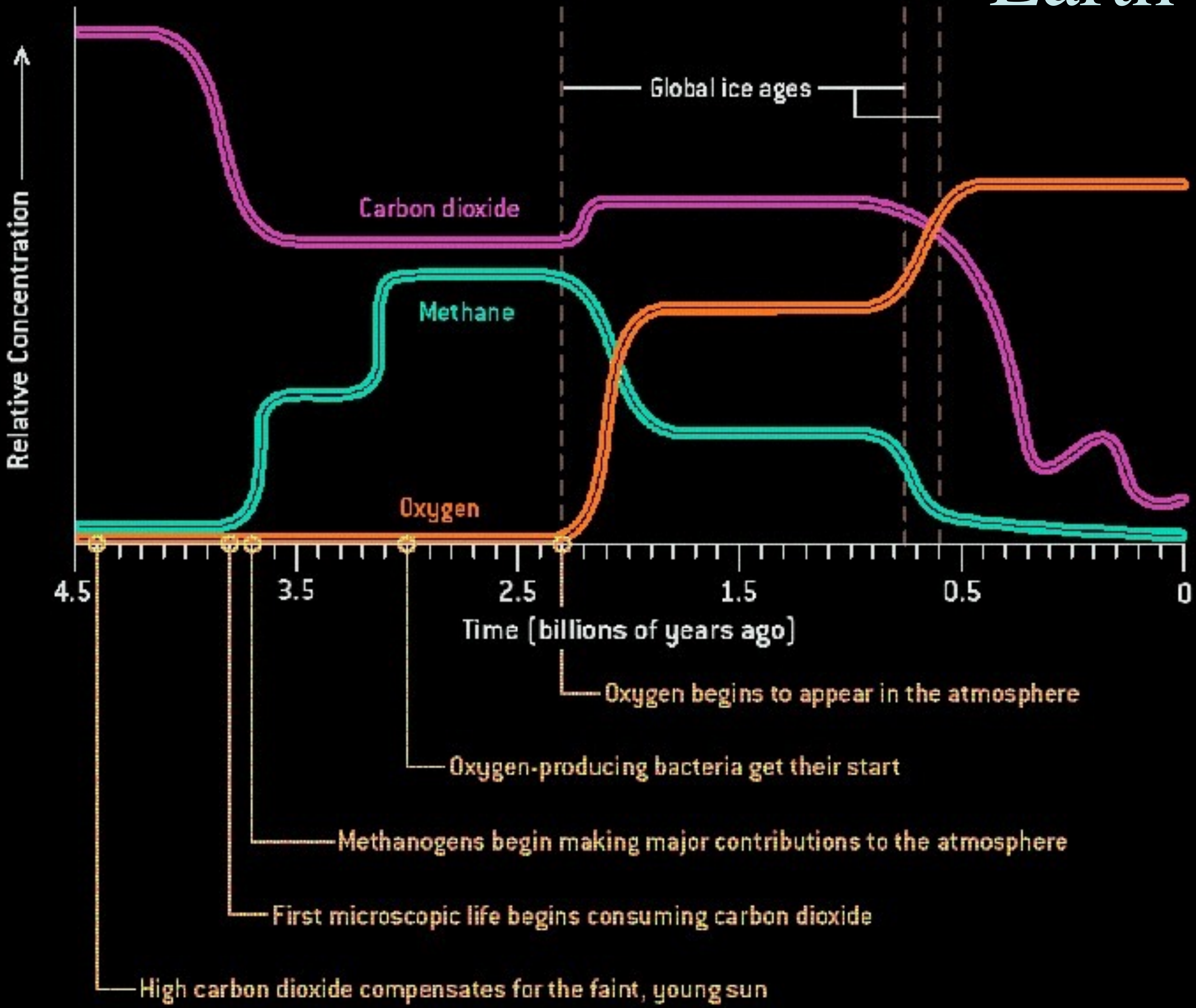
Schopf (1993)



3465 Ma, Western Australia

Real microfossils or overactive imagination?

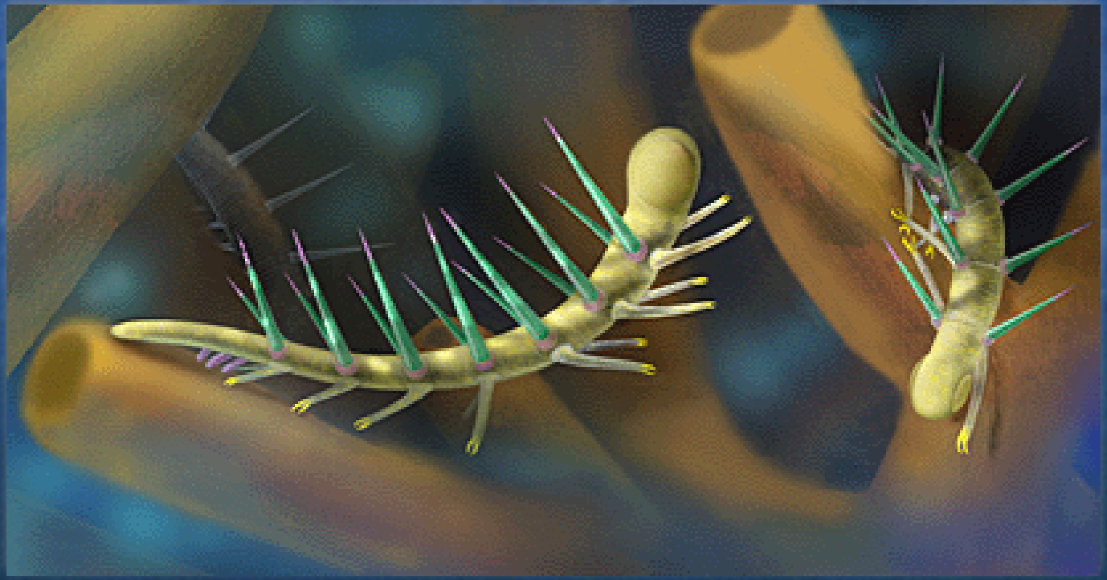
Earth over time



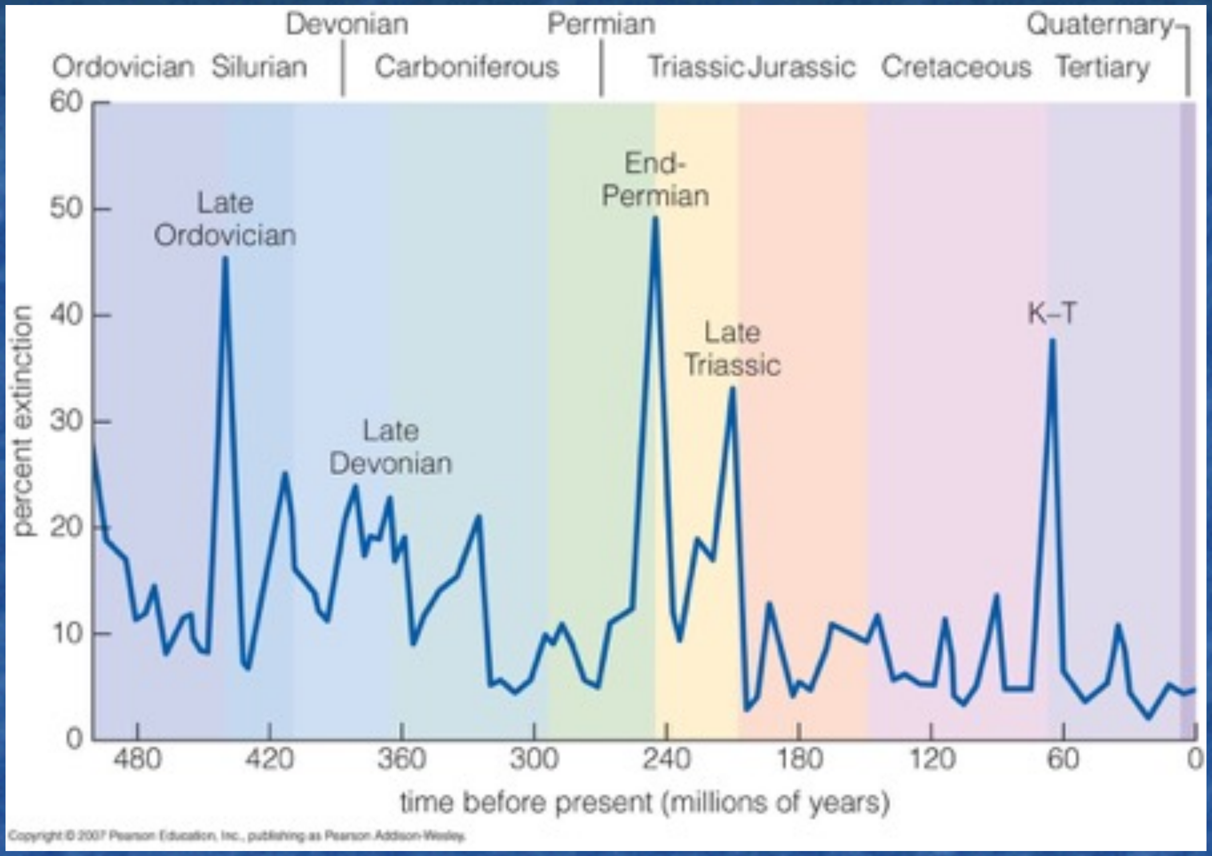
Kasting et al 2004

The Cambrian Explosion

- The Cambrian Explosion refers to the rapid emergence of diverse life-forms about 540 Myr ago
- Four keys factors which may have triggered this event:
  - rise in oxygen levels
  - increased genetic complexity
  - climate change (end of most recent Snowball Earth episode)
  - lack of predators

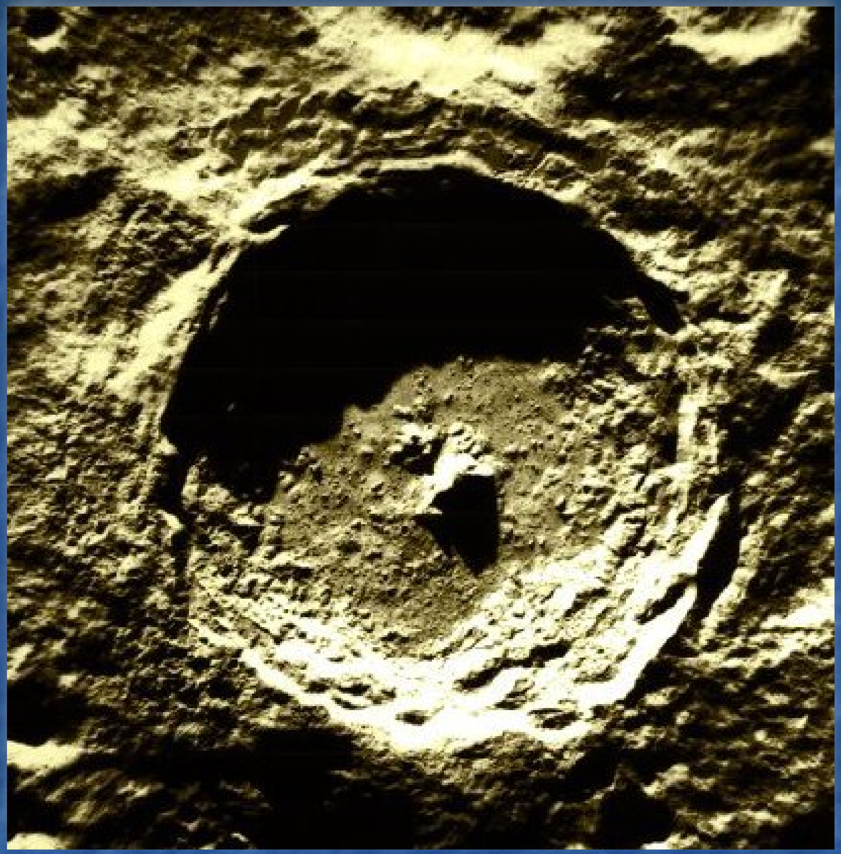


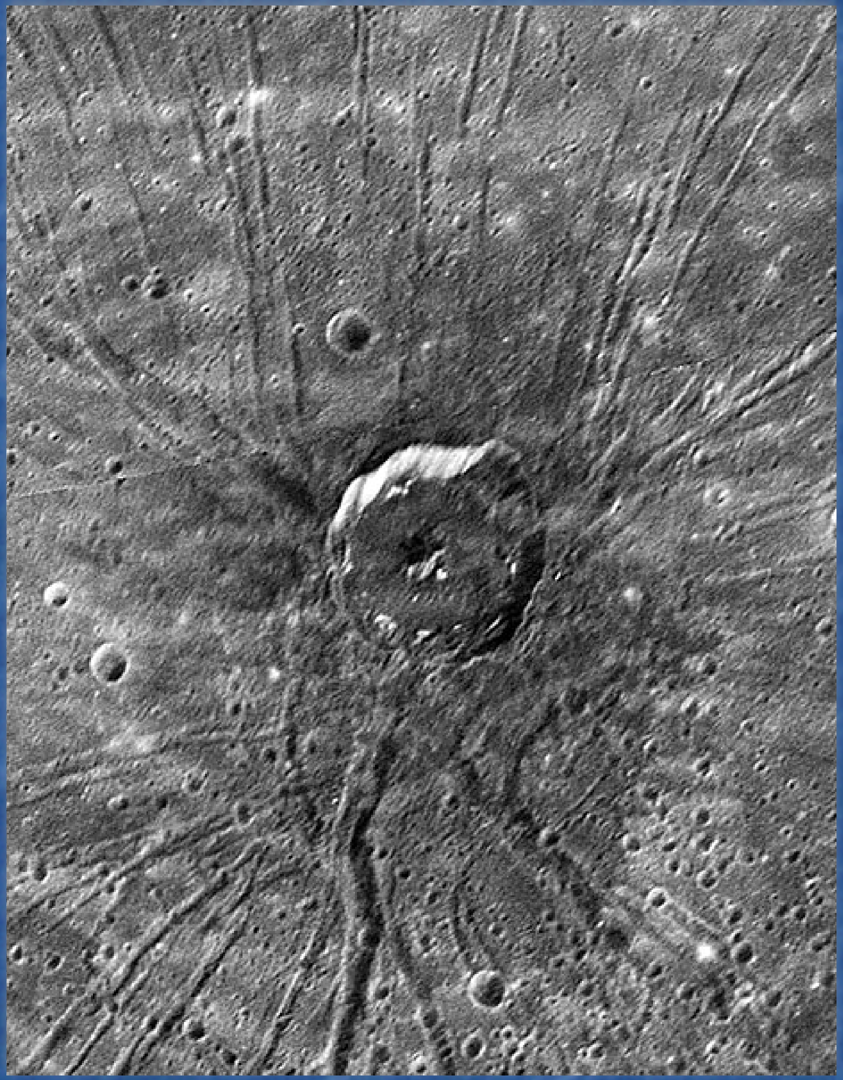
The KT impact

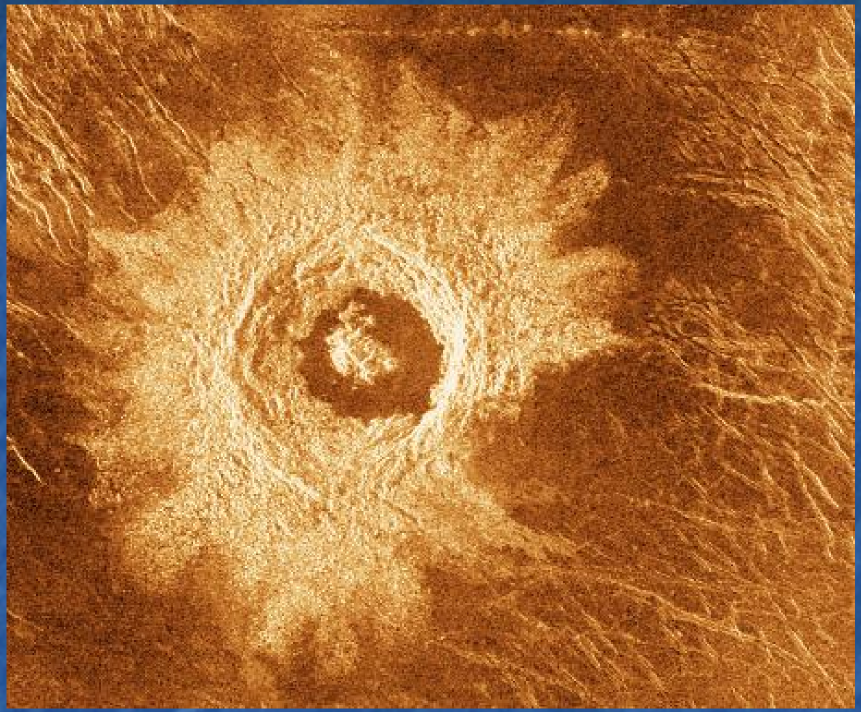


- Several mass extinction events have been observed in the fossil record since the Cambrian explosion.
- However, the KT event is also associated with the Iridium layer - a thin band of iridium rich deposits and ash.
- Iridium is rare in the Earths crust, it should sink to the Earth's core with the iron during differentiation. However, asteroids are rich in iridium.
- This led Luiz and Walter Alvarez to propose that the KT event was triggered by a massive impact (or series of impacts) by an asteroids.
- The impact debris (ash, and dust) would have spread throughout the atmosphere causing a global cooling lasting years or decades.
- The KT event marked the extinction of the dinosaurs.

Craters in the Inner Solar System



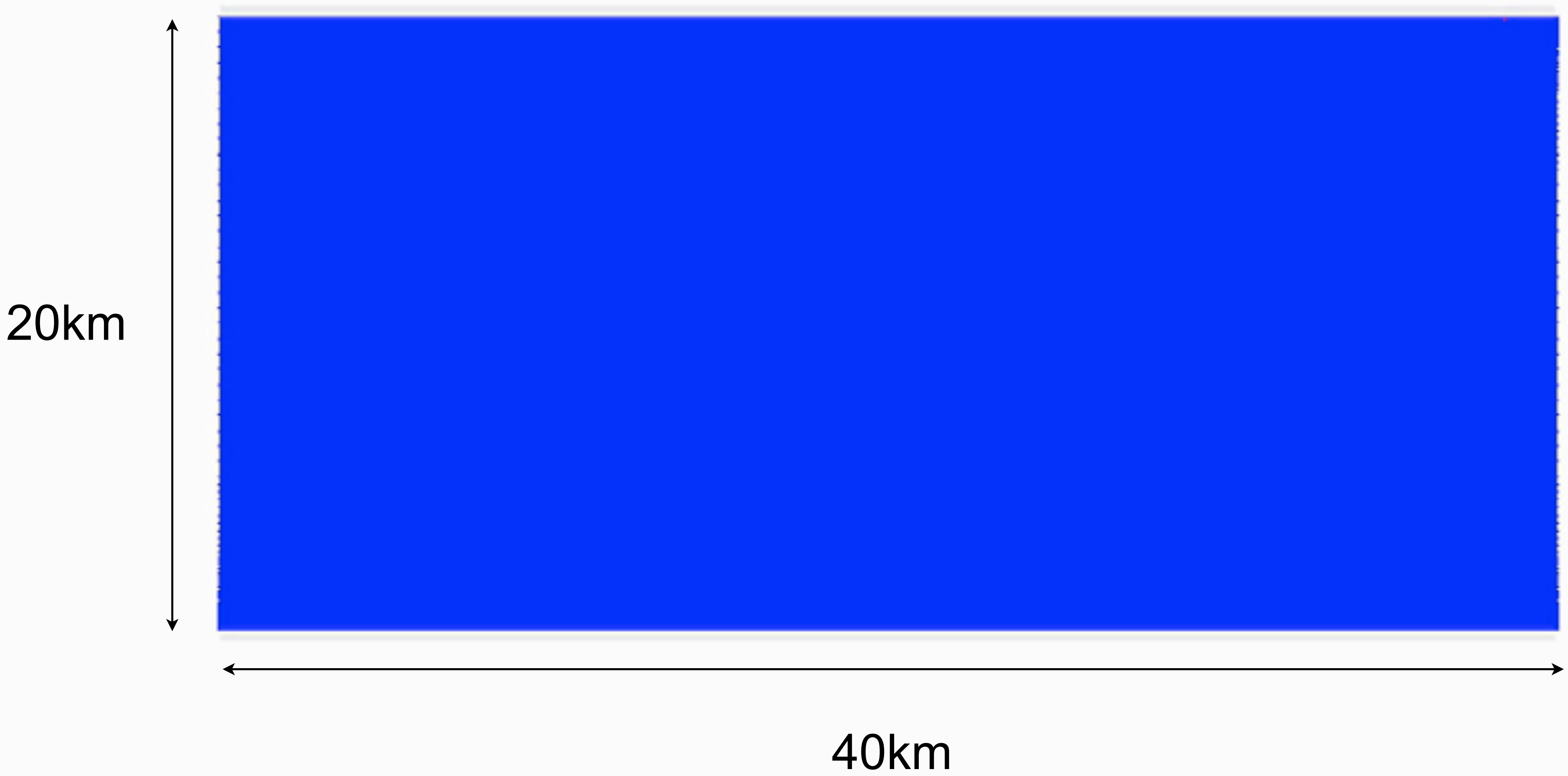




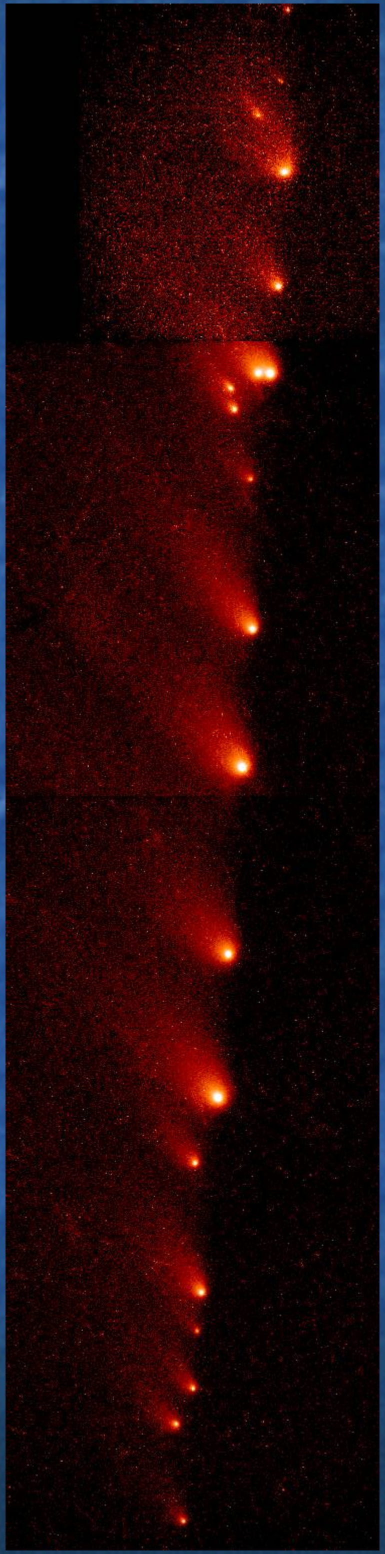
Tunguska:

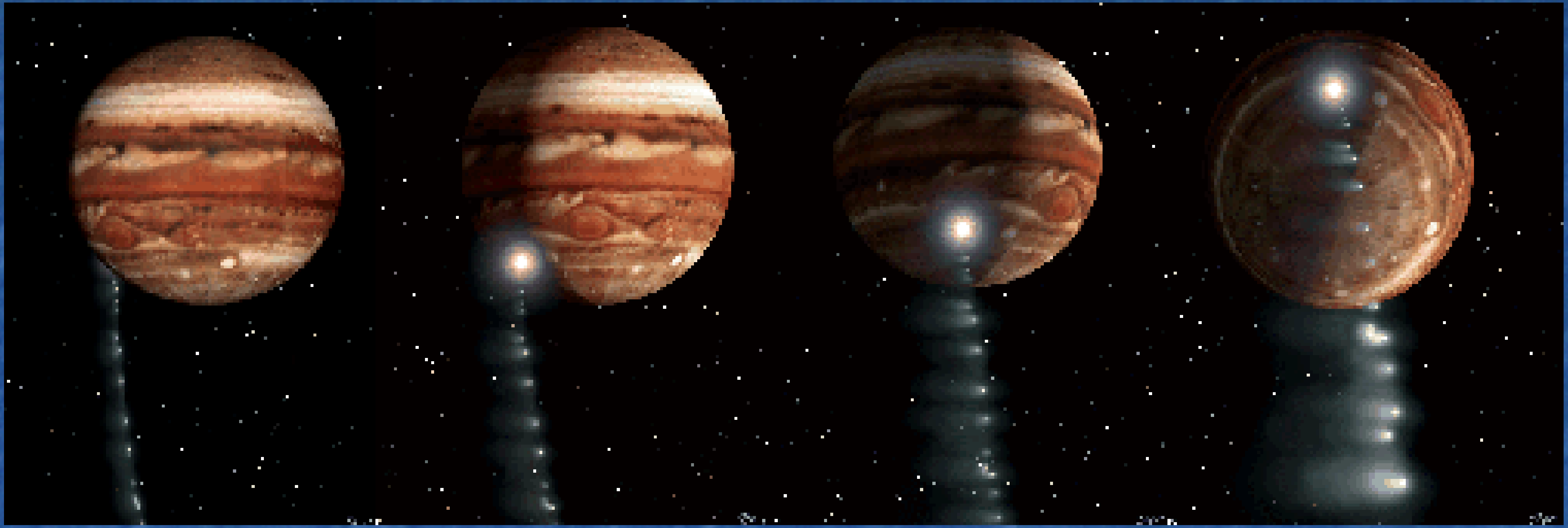
7.14am June 30th 1908

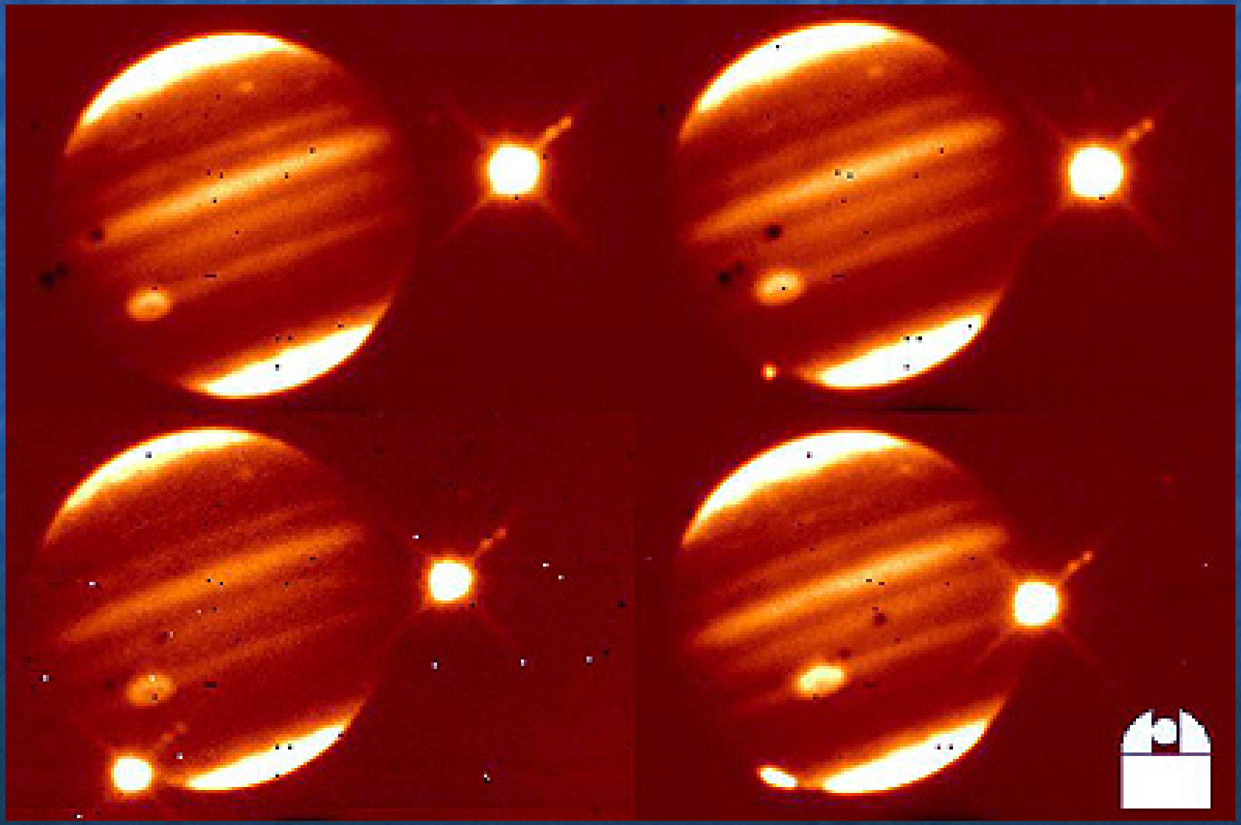
5 megaton asteroid airburst

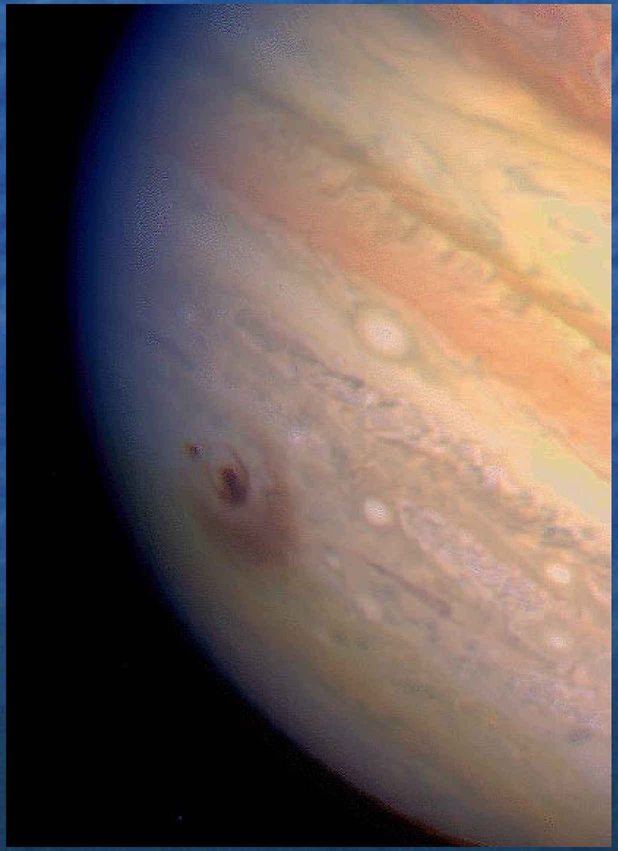


Comet Shoemaker-Levy 9 (July 1994)

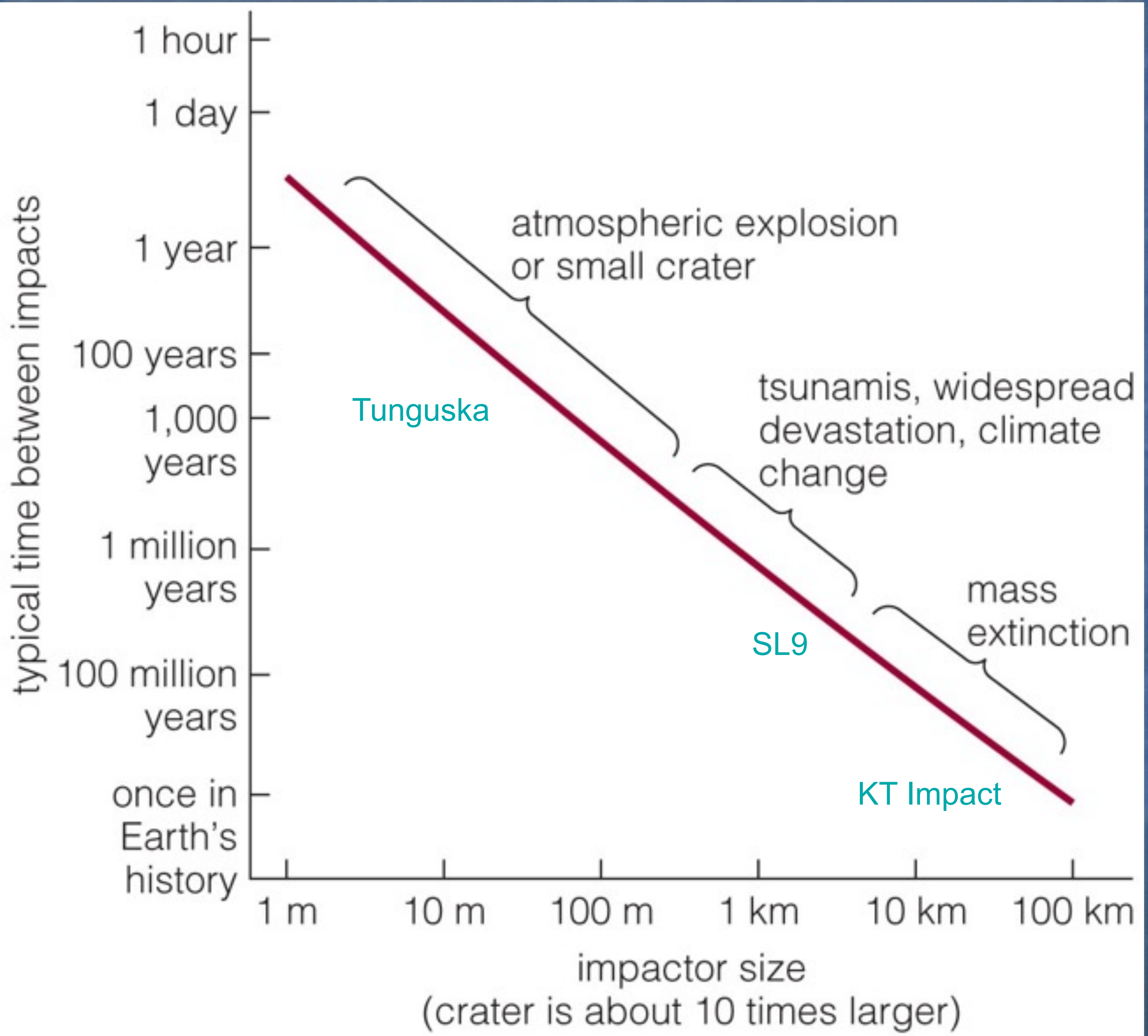








The Likelihood and Consequences of Impacts



How Much Warning Would We Have?

Comet Hyakutake (1997): 2 months

Comet Hale-Bopp (1997): 2 years

Comet McNaught (2007): 5 months

Comet Holmes (2007): 182 years

UPCOMING CLOSE APPROACHES TO EARTH

1 AU = ~150 million kilometers
1 LD = Lunar Distance = ~384,000 kilometers

Object Name	Close Approach Date	CA Distance* (AU)	CA Distance* (LD)	Estimated Diameter**	H (mag)	Relative Velocity (km/s)
(2016 PR39)	2016-Sep-06	0.0474	18.5	37 m - 82 m	24.3	11.01
(2016 JN)	2016-Sep-06	0.1740	67.7	54 m - 120 m	23.4	9.49
250458 (2004 BO41)	2016-Sep-07	0.0999	38.9	700 m - 1.6 km	17.9	24.68
(2016 PD1)	2016-Sep-07	0.0596	23.2	43 m - 97 m	23.9	5.42
(2016 RB1)	2016-Sep-07	0.0003	0.1	7.3 m - 16 m	27.8	8.13
(2016 GD135)	2016-Sep-07	0.1556	60.5	180 m - 400 m	20.8	12.38
(2014 DN7)	2016-Sep-08	0.1676	65.2	190 m - 430 m	20.7	26.02
(2016 QN44)	2016-Sep-09	0.0736	28.7	90 m - 200 m	22.3	15.04
(2016 RV1)	2016-Sep-09	0.0487	19.0	29 m - 64 m	24.8	11.39
(2016 QD45)	2016-Sep-09	0.1941	75.5	39 m - 88 m	24.2	5.46
(2016 QS44)	2016-Sep-10	0.0205	8.0	35 m - 79 m	24.4	17.38
(2015 KE)	2016-Sep-10	0.0383	14.9	14 m - 31 m	26.4	2.16
(2012 WK4)	2016-Sep-10	0.1448	56.4	150 m - 330 m	21.3	7.34
(2004 SW26)	2016-Sep-11	0.1170	45.5	19 m - 43 m	25.7	12.64
(2016 QM44)	2016-Sep-11	0.1311	51.0	50 m - 110 m	23.6	11.32
(2016 PR26)	2016-Sep-11	0.0841	32.7	49 m - 110 m	23.7	6.68
(2009 BK2)	2016-Sep-11	0.0760	29.6	23 m - 52 m	25.3	8.84
(2016 QK10)	2016-Sep-12	0.1062	41.3	26 m - 57 m	25.1	4.44
(2016 LX48)	2016-Sep-12	0.0455	17.7	350 m - 790 m	19.4	10.77
(2016 QY10)	2016-Sep-14	0.1828	71.2	53 m - 120 m	23.5	5.12
(2016 NF33)	2016-Sep-14	0.1833	71.3	150 m - 340 m	21.2	5.38
(2016 QM10)	2016-Sep-14	0.0936	36.4	78 m - 170 m	22.7	8.24
(2016 FD22)	2016-Sep-14	0.1433	55.8	46 m - 100 m	23.8	14.76
(2016 PJ66)	2016-Sep-14	0.1910	74.3	97 m - 220 m	22.2	7.15
469513 (2003 QR79)	2016-Sep-15	0.1838	71.5	180 m - 410 m	20.8	9.96
471240 (2011 BT15)	2016-Sep-15	0.0509	19.8	120 m - 260 m	21.8	8.17
(2001 RU17)	2016-Sep-15	0.1468	57.1	130 m - 300 m	21.5	8.31
(2016 FR12)	2016-Sep-16	0.1863	72.5	32 m - 71 m	24.6	8.85
(2008 TP26)	2016-Sep-17	0.1145	44.6	46 m - 100 m	23.8	9.58
(2016 QL44)	2016-Sep-17	0.0093	3.6	27 m - 61 m	24.9	13.86
(2016 QS11)	2016-Sep-18	0.0313	12.2	19 m - 43 m	25.7	3.76

Implications for life in the Universe

- Volcanic outgassing (surface or deep sea) provides organic chemical factory.
- Evidence points to life arising as early as was practically possible (after the heavy bombardment phase).
- No evidence for a second genesis.
- Life has altered the composition of the Earth's atmosphere.
- Without methanogens and photosynthesis would Earth have been subject to a runaway greenhouse effect - similar to Venus?