11th Annual Dr. Ed Waits Respiratory Care Conference
June 21, 2023

CELLULAR RESPIRATION IN THE AEROBIC WORLD

AFTER A LONG BEGINNING ON AN ANAEROBIC PLANET

OXYGEN AND IRON

James R. Boogaerts, MD, PhD, FACC
UAB Division of Cardiovascular Disease

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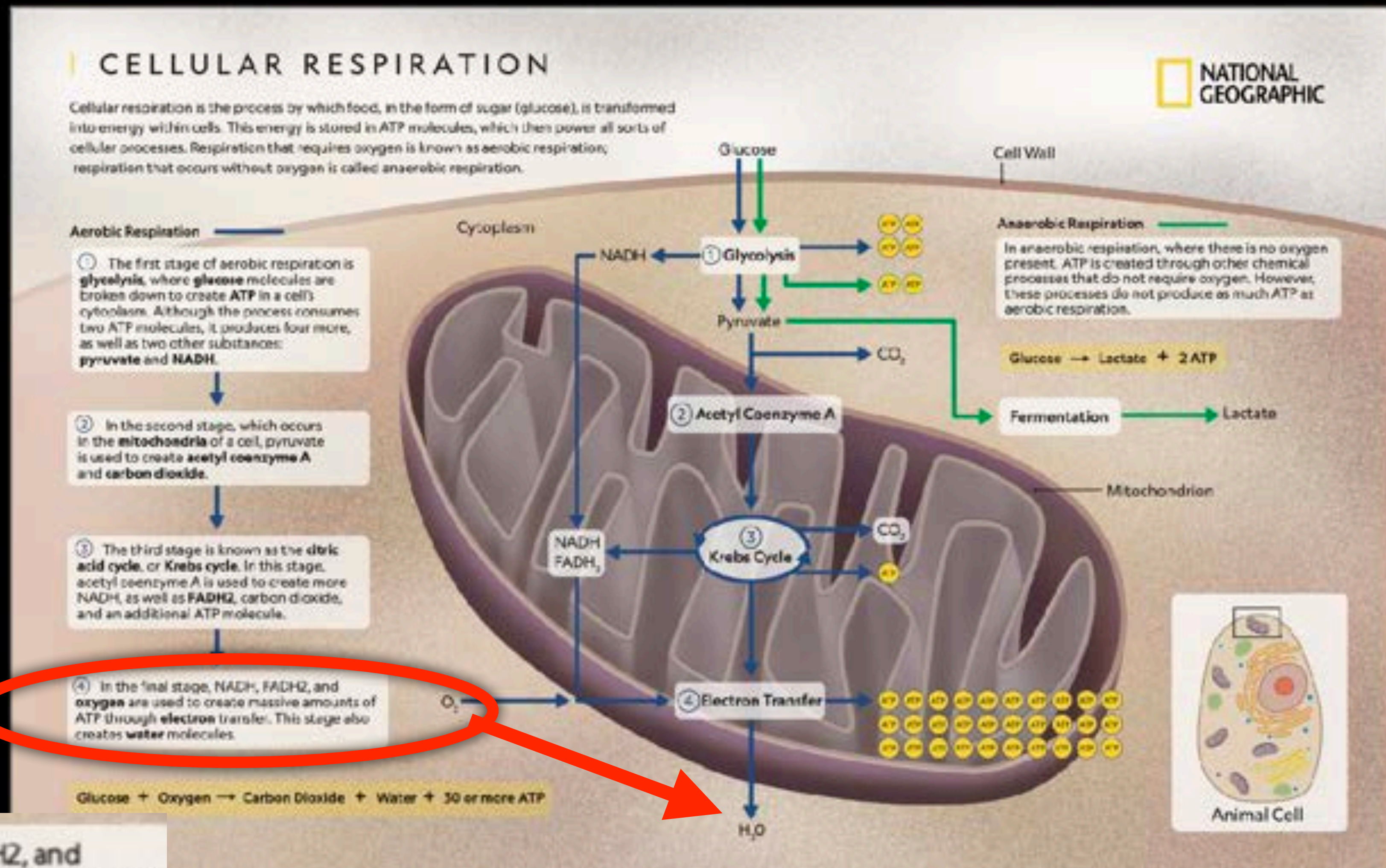


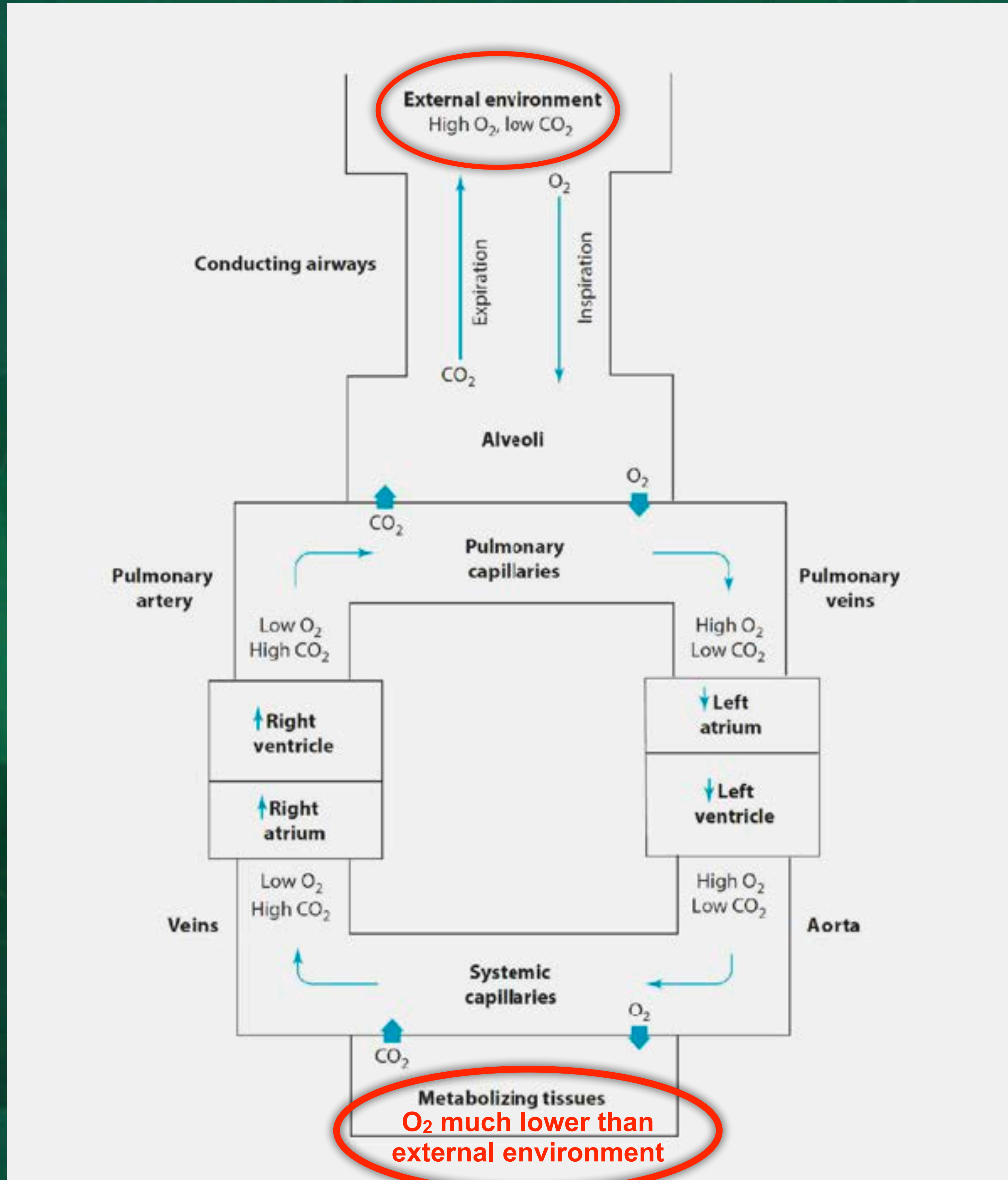
④ In the final stage, NADH, FADH2, and **oxygen** are used to create massive amounts of ATP through **electron** transfer. This stage also creates **water** molecules.

source

AEROBIC RESPIRATION

Aerobic respiration requires oxygen. This is the reason why we breathe oxygen in from the air. This type of respiration efficiently releases a large amount of energy from glucose that can be stored as ATP. Aerobic respiration happens all the time in animals and plants, where most of the reactions occur in the mitochondria. Even some prokaryotes can perform aerobic respiration (although since prokaryotes don't contain mitochondria, the reactions are slightly different). The overall chemical formula for aerobic respiration can be written as:

$$C_6H_{12}O6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{(approximately) } 38\ ATP$$



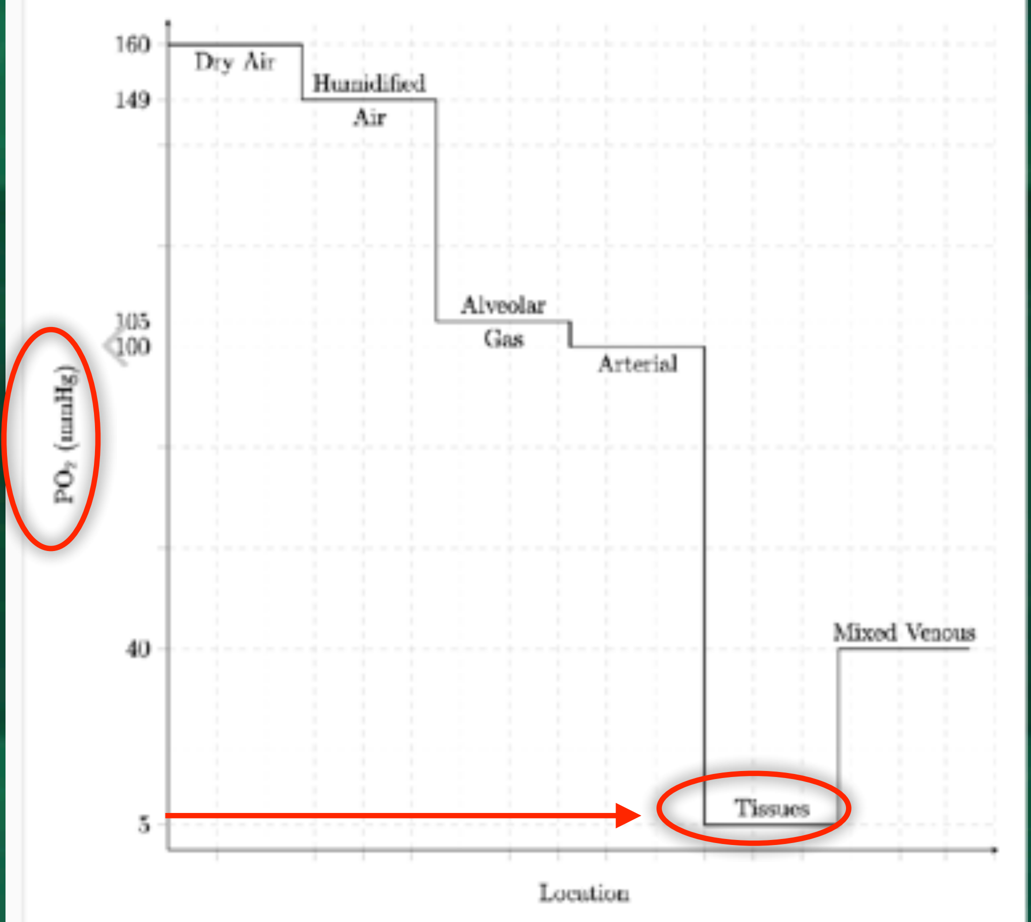
Pulmonary Physiology, Tenth Edition
by Michael Levitzky | Aug 30, 2022

Oxygen Cascade

The **oxygen cascade** describes the transfer of oxygen from air to mitochondria.

- In each step of the cascade the PaO_2 falls

  It demonstrates that oxygen delivery to tissues relies on the **passive transfer** of gas down **partial pressure gradients**.
- The steps of the cascade are:
  - Dry atmospheric gas
  - Humidified tracheal gas
  - Alveolar gas
  - Arterial blood
  - Mitochondria
  - Venous blood



Atmospheric Gas

Atmospheric partial pressure of oxygen is a function of barometric pressure and the FiO_2:

- $PO_2 = P_B \times FiO_2$, where:
  - P_B is 760mmHg
  - FiO_2 is 0.21
- Therefore, PO_2 = **160mmHg**

PI_{N2}: 590 mmHg
PI_{O2}: 160 mmHg
PI_{Ar}: 7 mmHg
PI_{CO2}: 0.3 mmHg

PI_{O2}: 160 mmHg

tracheal humidity 149 mmHg

Alveolar Gas

Ideal alveolar PO_2 is calculated using the **alveolar gas equation**:

$P_AO_2 = P_iO_2 - \frac{P_aCO_2}{R} + F$, where:

- P_AO_2 is the alveolar partial pressure of oxygen
- P_iO_2 is the inspired partial pressure of oxygen
- P_aCO_2 is the arterial partial pressure of carbon dioxide
- R is the respiratory quotient, where $R = \frac{\text{Volume of } CO_2 \text{ produced}}{\text{Volume of } O_2 \text{ consumed}}$

respiratory PaCO2 → ↓ PaO2

Arterial Blood

- Normal arterial PO_2 is 100mmHg

PaO2: 100 mmHg

Mitochondria

- PO_2 varies with metabolic activity, but typically quoted as 5mmHg
- The **Pasteur point** is the partial pressure of oxygen at which oxidative phosphorylation ceases, and is **~1mmHg**

PaO2: 5 mmHg

Venous Blood

- PO_2 is greater than mitochondrial PO_2

  Mixed venous blood typically quoted as 40mmHg.
- Higher than mitochondria as not all arterial blood travels through capillary beds

PaO2: 40mmHg

LIFE IN THE FASTLANE

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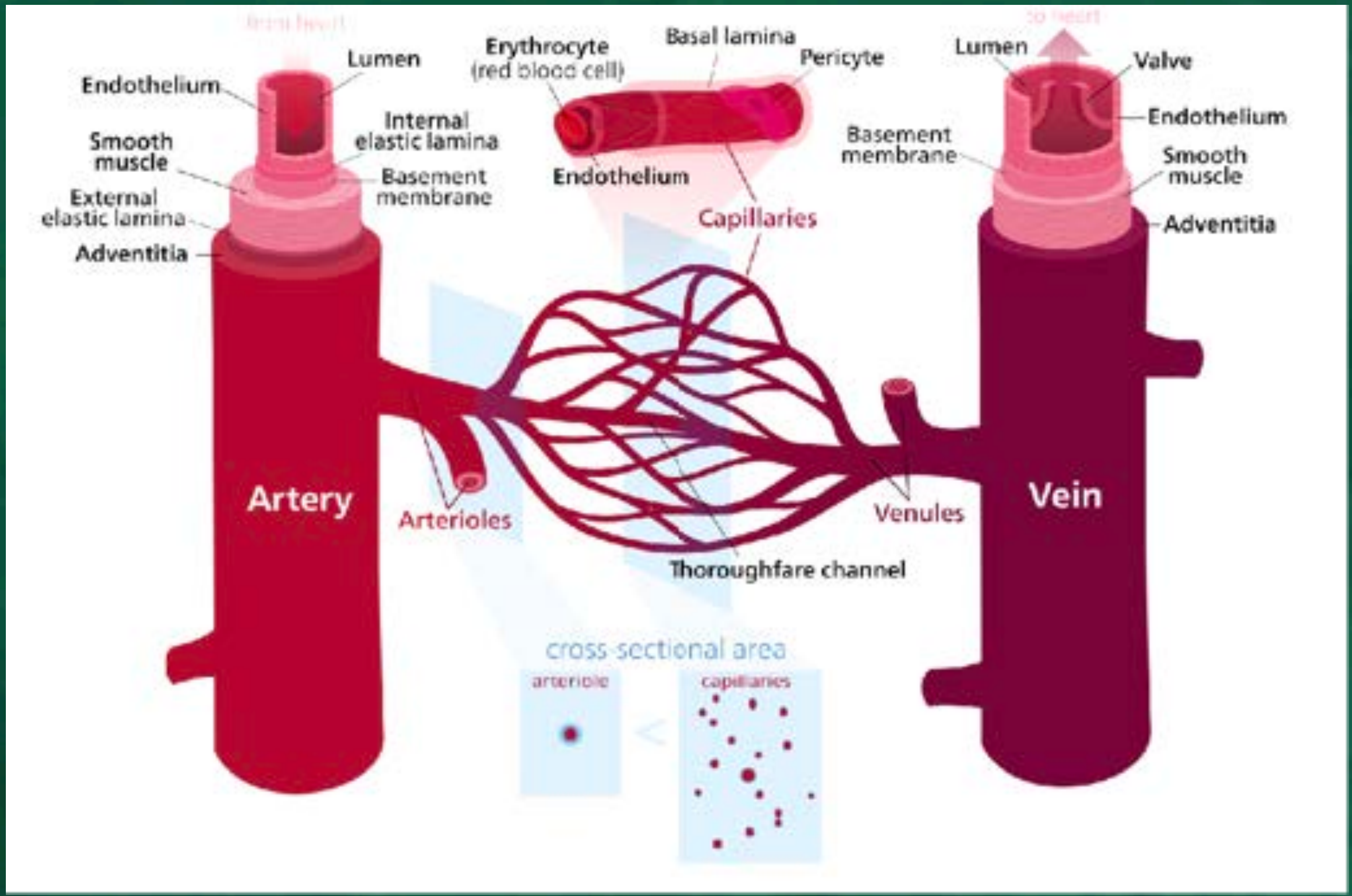
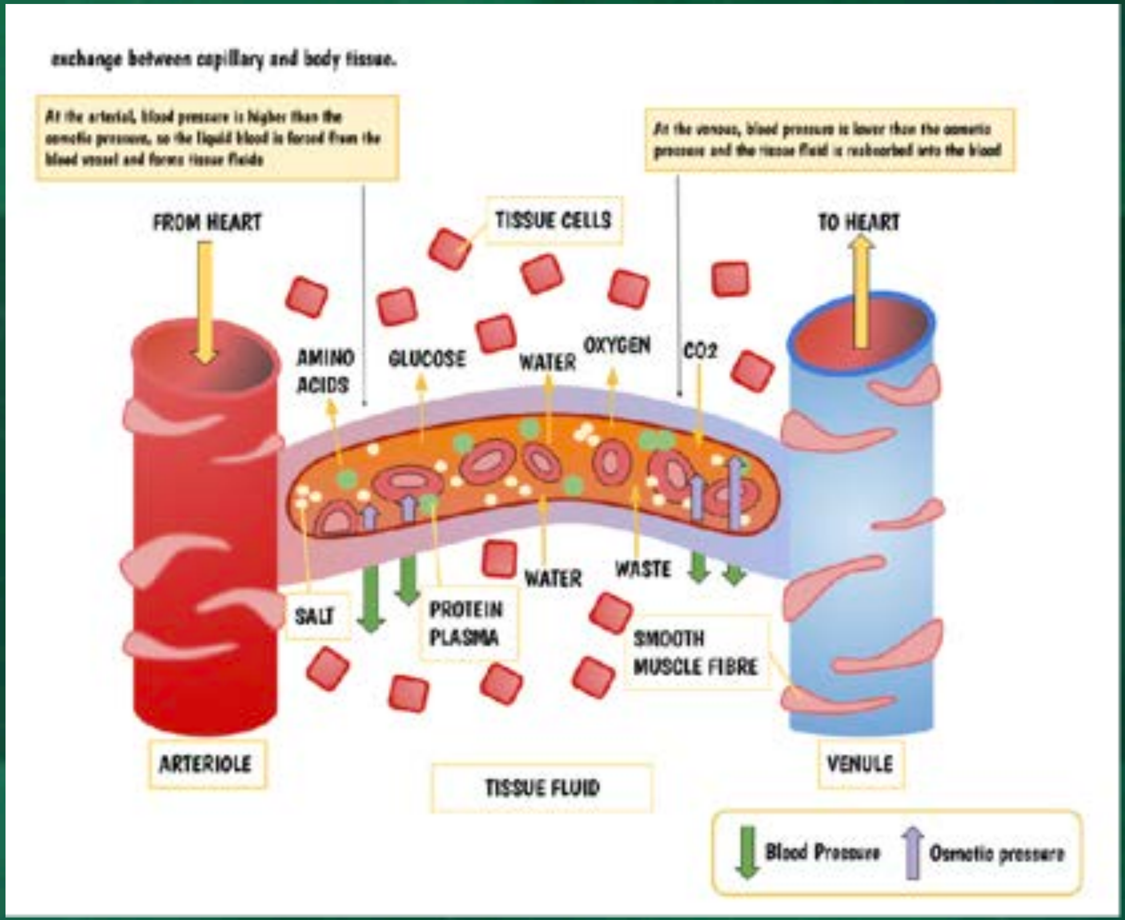
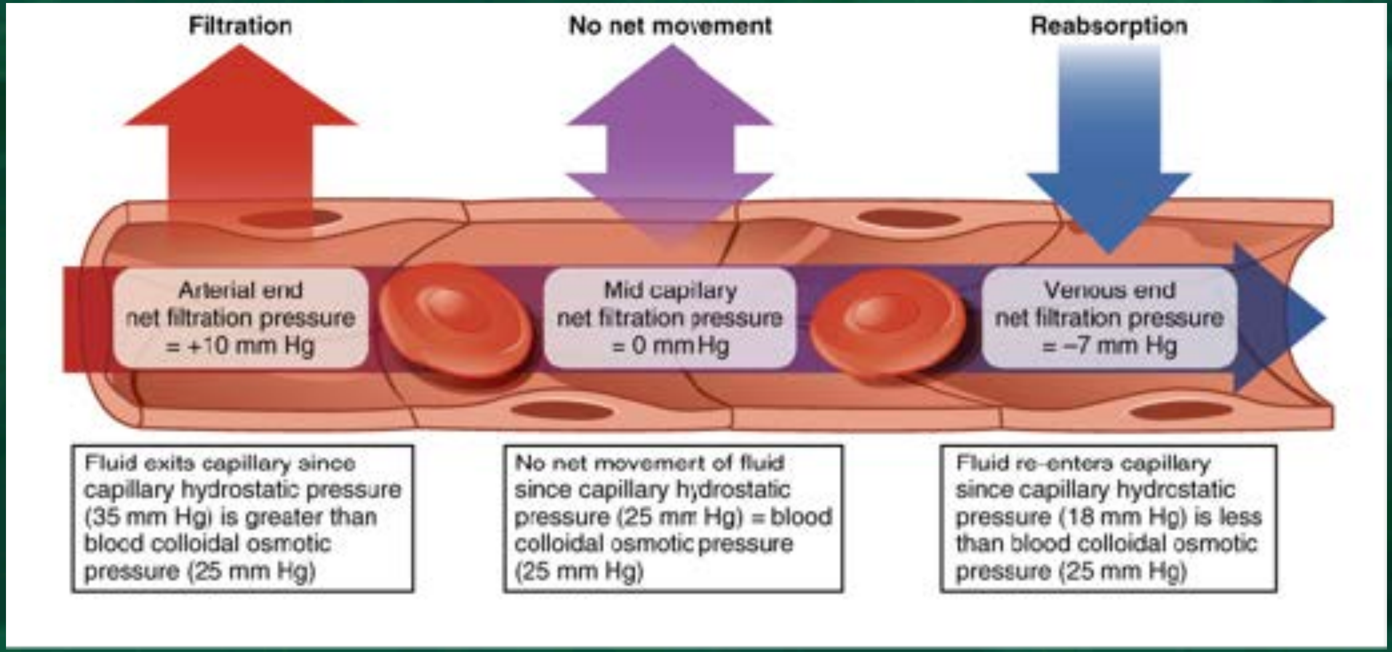
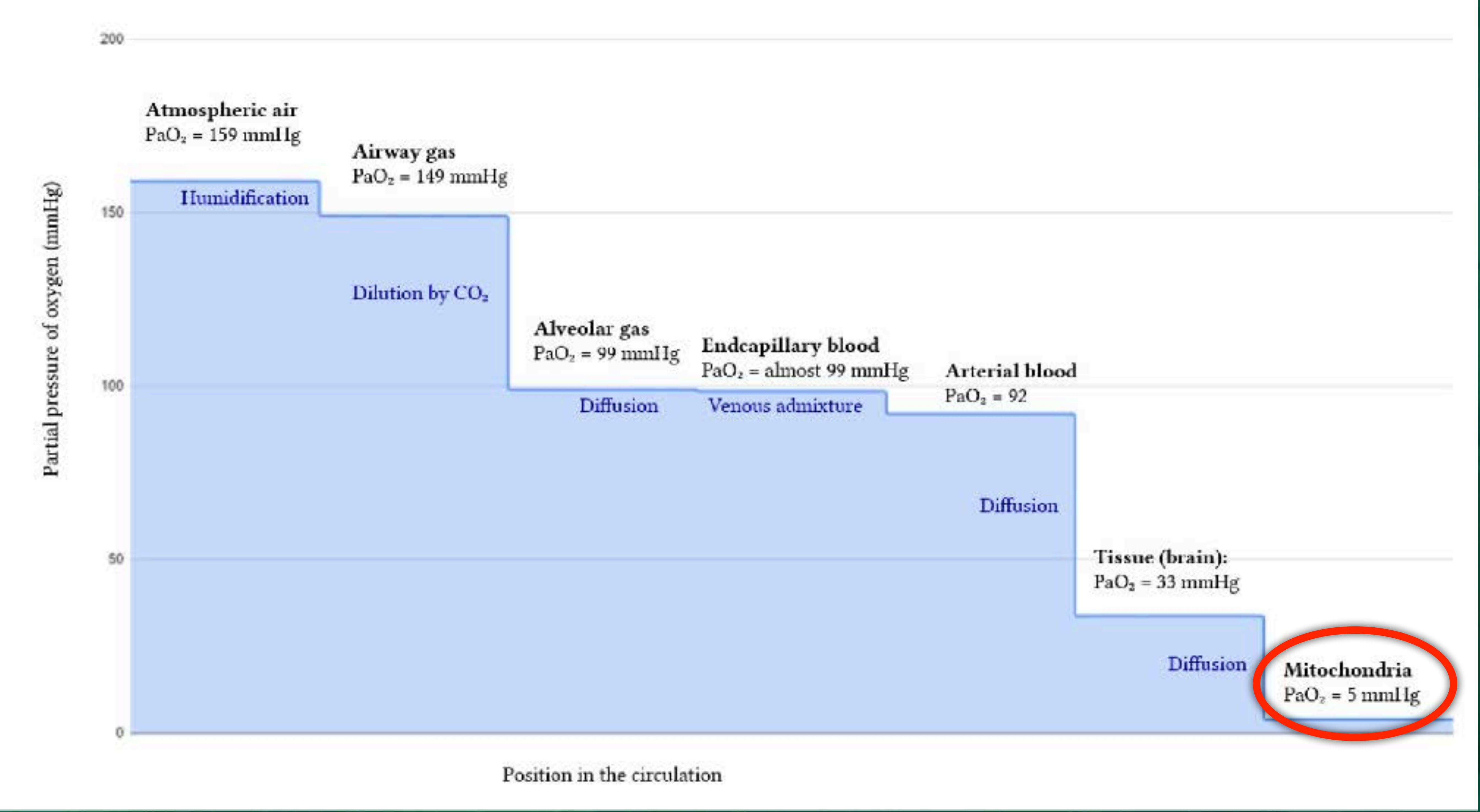






https://en.wikipedia.org/wiki/capillary


Partial pressure of oxygen (mmHg)
200
150
100
50
0
Atmospheric air
PaO_2 = 159 mmHg
Humidification
Airway gas
PaO_2 = 149 mmHg
Dilution by CO_2
Alveolar gas
PaO_2 = 99 mmHg
Diffusion
Endcapillary blood
PaO_2 = almost 99 mmHg
Venous admixture
Arterial blood
PaO_2 = 92
Diffusion
Tissue (brain):
PaO_2 = 33 mmHg
Diffusion
Mitochondria
PaO_2 = 5 mmHg
Position in the circulation

10th Annual Dr. Louis S. Pappas Educational Seminar
June 10, 2023

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Dr. Pappas especially loved hiking and fishing in the Grand Tetons and Glacier National Park.

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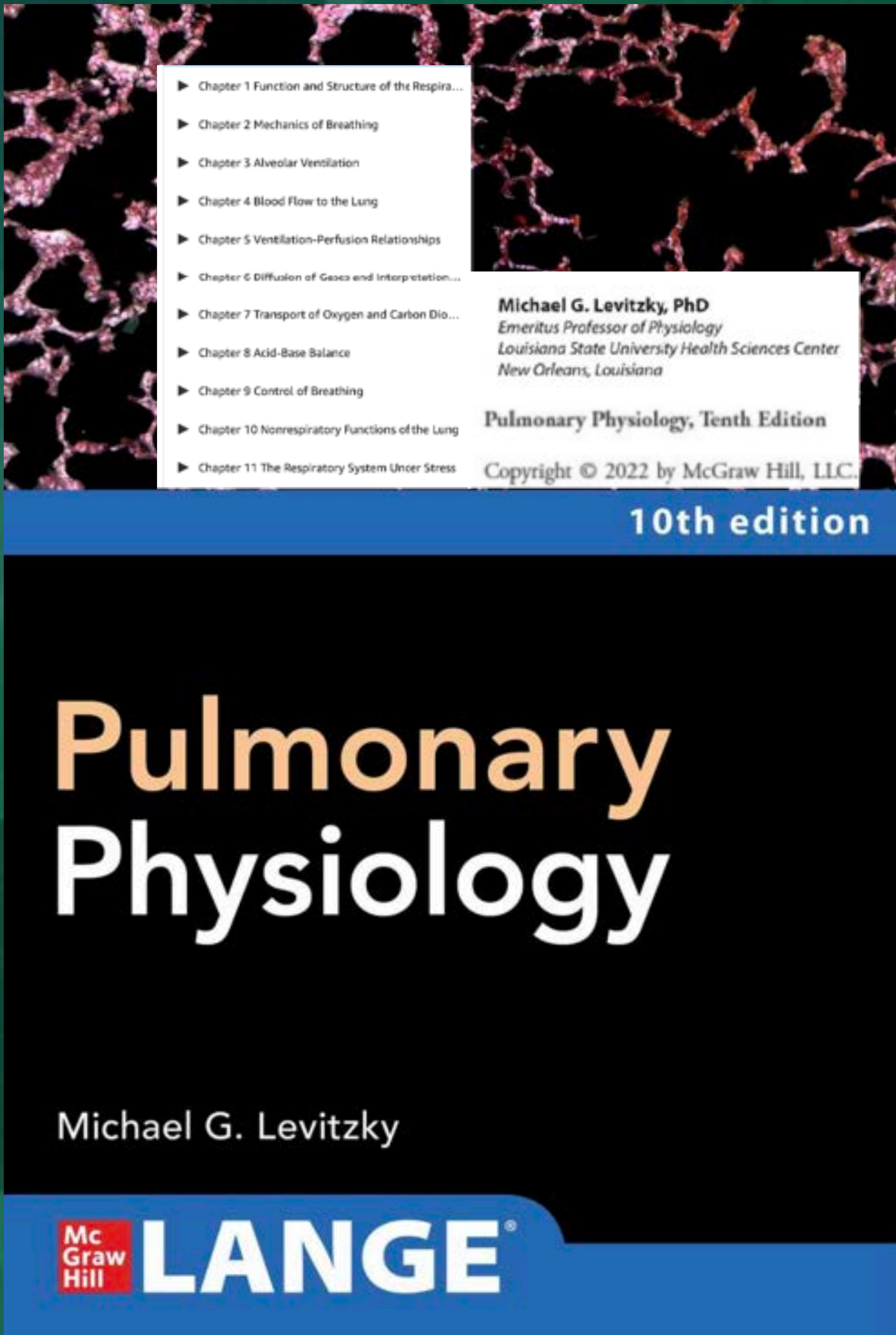


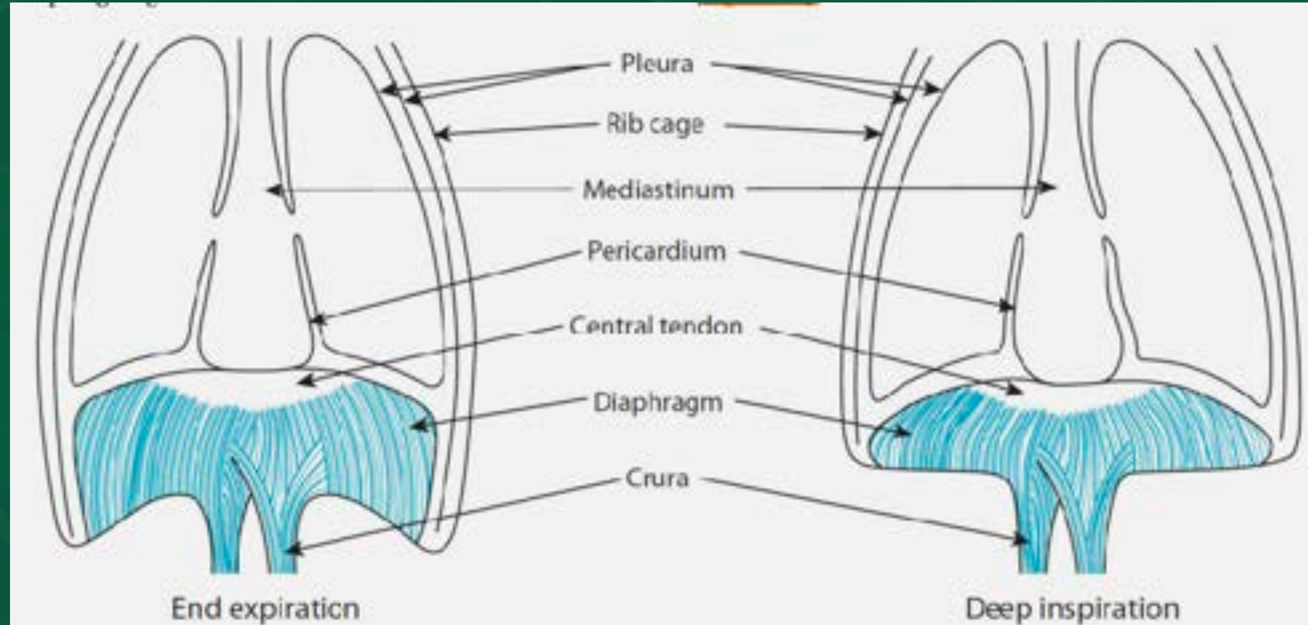
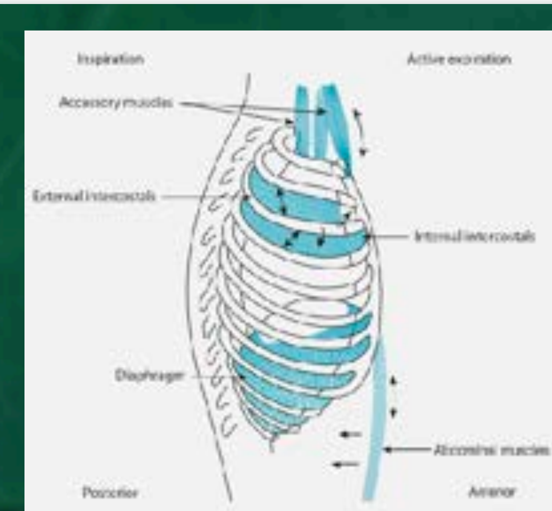


Figure 2–3. Illustration of the actions of diaphragmatic contraction in expanding the thoracic cavity.



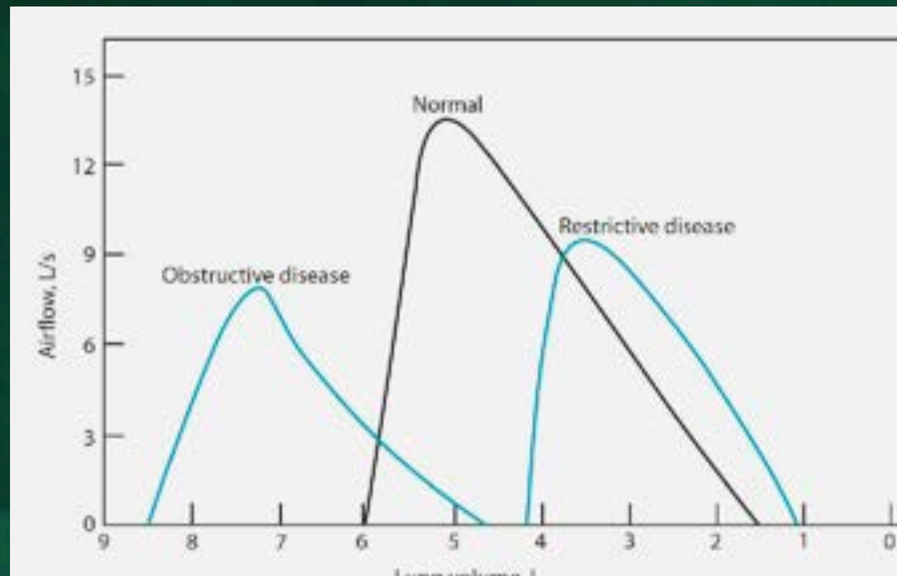


Figure 2–25. Maximal expiratory flow-volume curves representative of obstructive and restrictive diseases.

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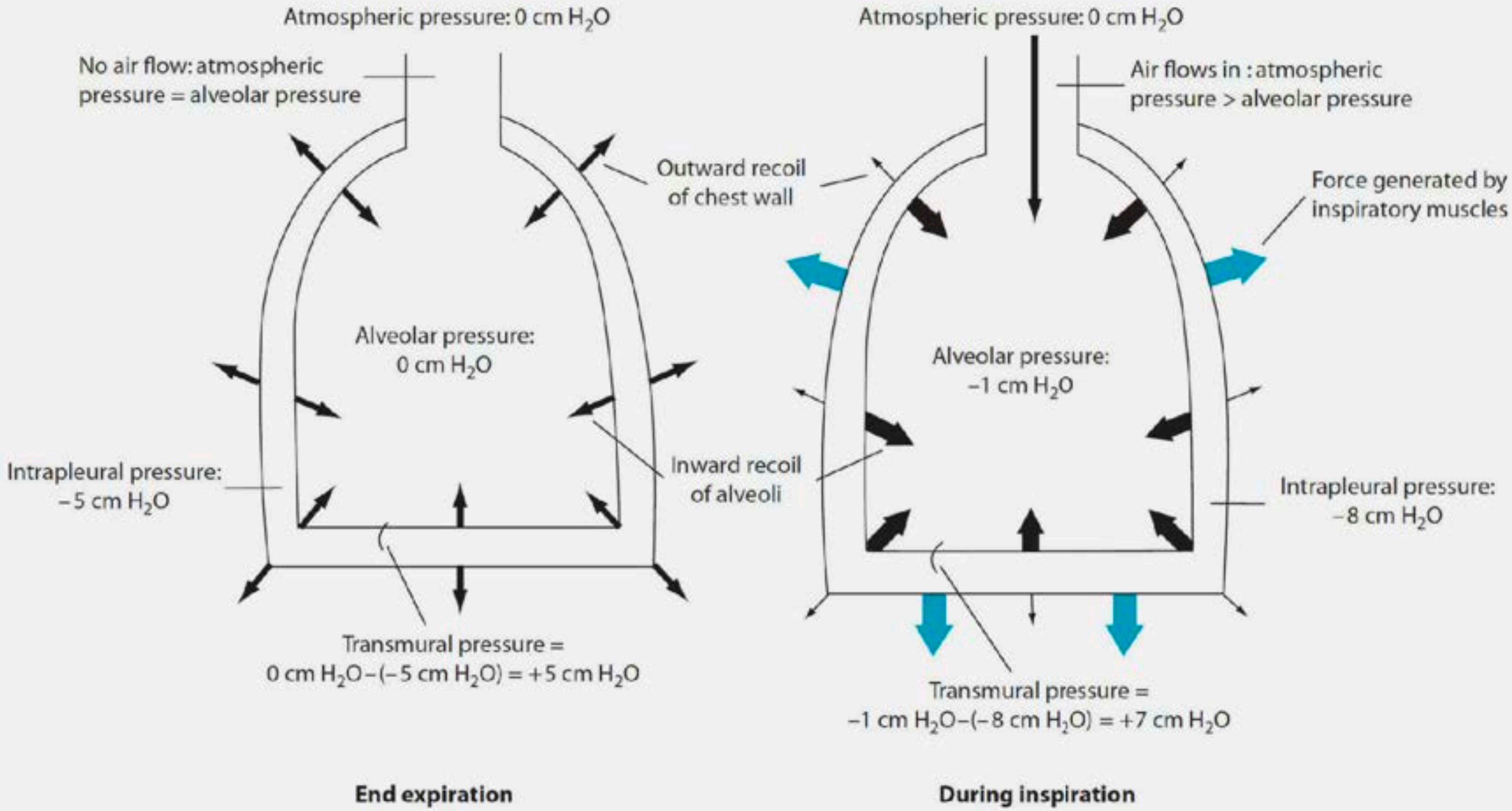
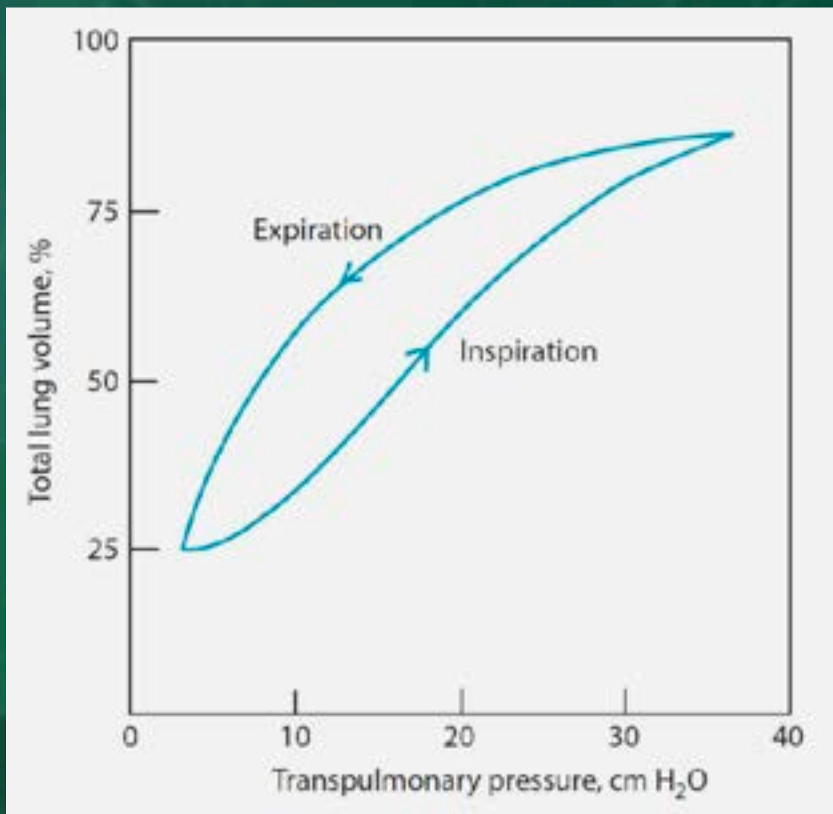


Figure 2–1. Representation of the interaction of the lung and chest wall. *Left:* At end expiration, the muscles of respiration are relaxed. The inward elastic recoil of the lung is balanced by the outward elastic recoil of the chest wall. Intrapleural pressure is −5 cm H_2O; alveolar pressure is 0. The transmural pressure difference across the alveolus is therefore 0 cm H_2O −(−5 cm H_2O), or 5 cm H_2O. Since alveolar pressure is equal to atmospheric pressure, no airflow occurs. *Right:* During inspiration, contraction of the muscles of inspiration causes intrapleural pressure to become more negative. The transmural

Pulmonary Physiology, Tenth Edition
by Michael Levitzky | Aug 30, 2022



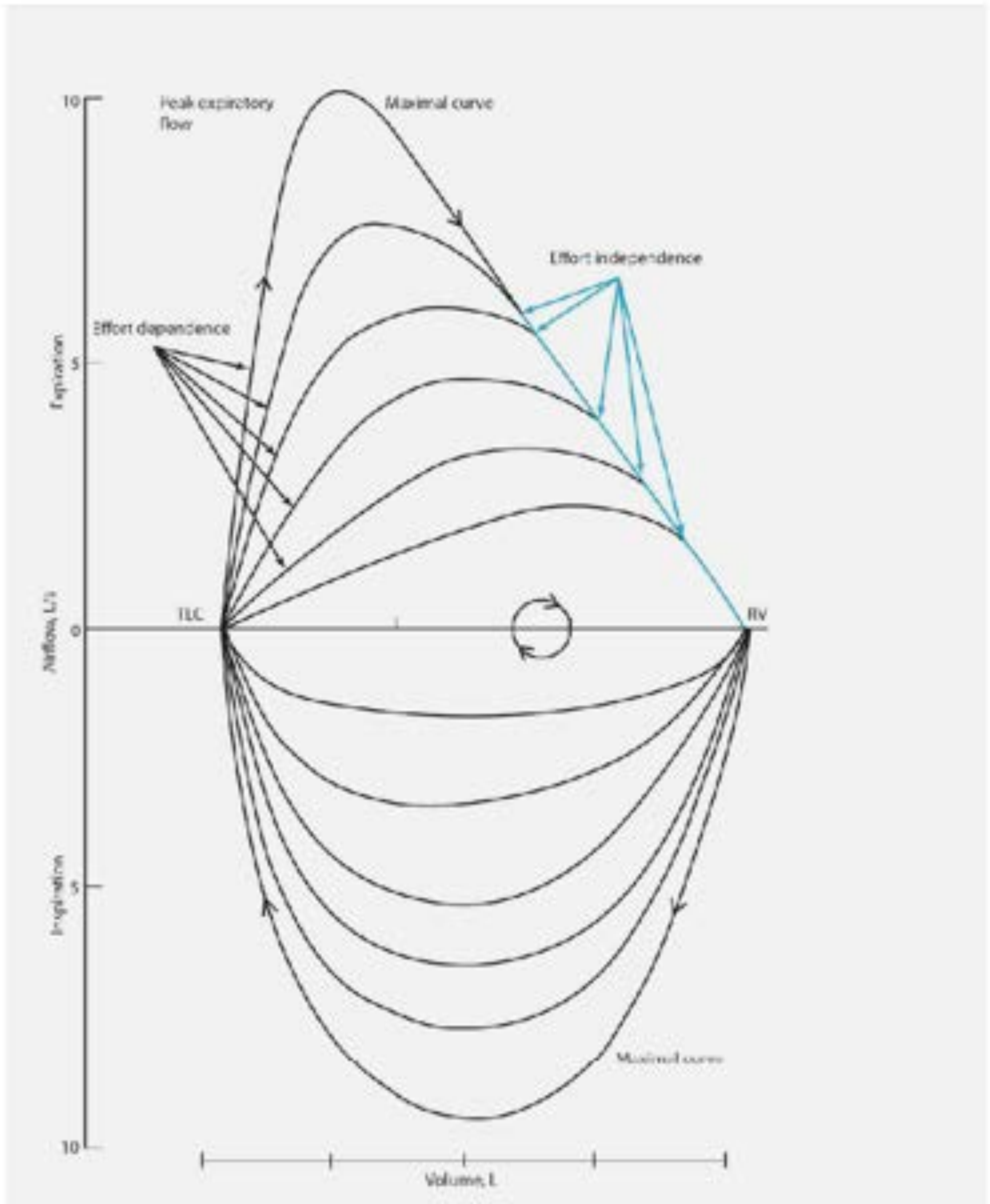
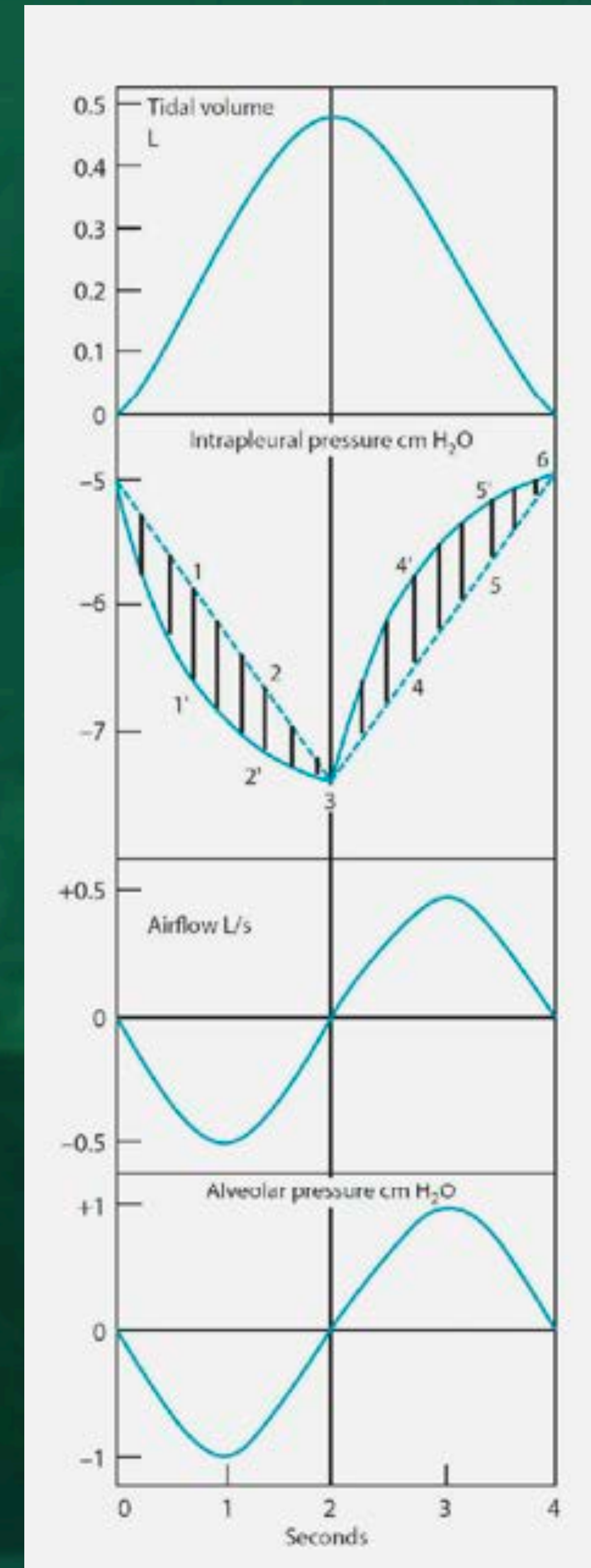


Figure 2–24. Flow-volume curves of varying intensities, demonstrating effort dependence at high lung volumes and effort independence at low lung volumes. Note that there is normally no effort independence in inspiration. The small loop represents a normal tidal volume. The peak expiratory flow (PEF) is labeled for the maximal expiratory curve. TLC = total lung capacity; RV = residual volume



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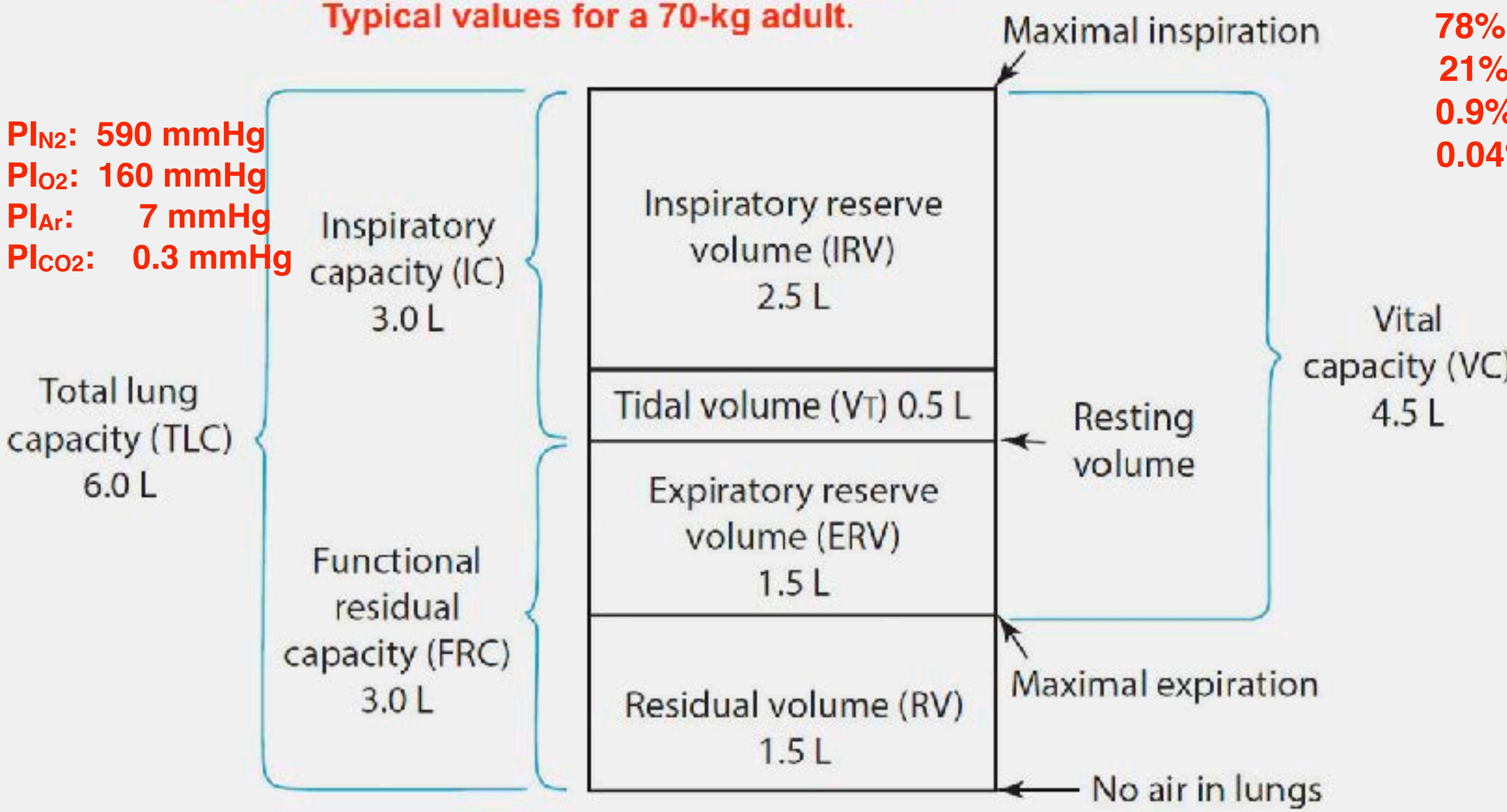
The standard lung volumes and capacities.
Typical values for a 70-kg adult.

Current atmosphere:

78% N_2
21% O_2
0.9% Ar
0.04% CO_2

PI_{N2}: 590 mmHg
PI_{O2}: 160 mmHg
PI_{Ar}: 7 mmHg
PI_{CO2}: 0.3 mmHg



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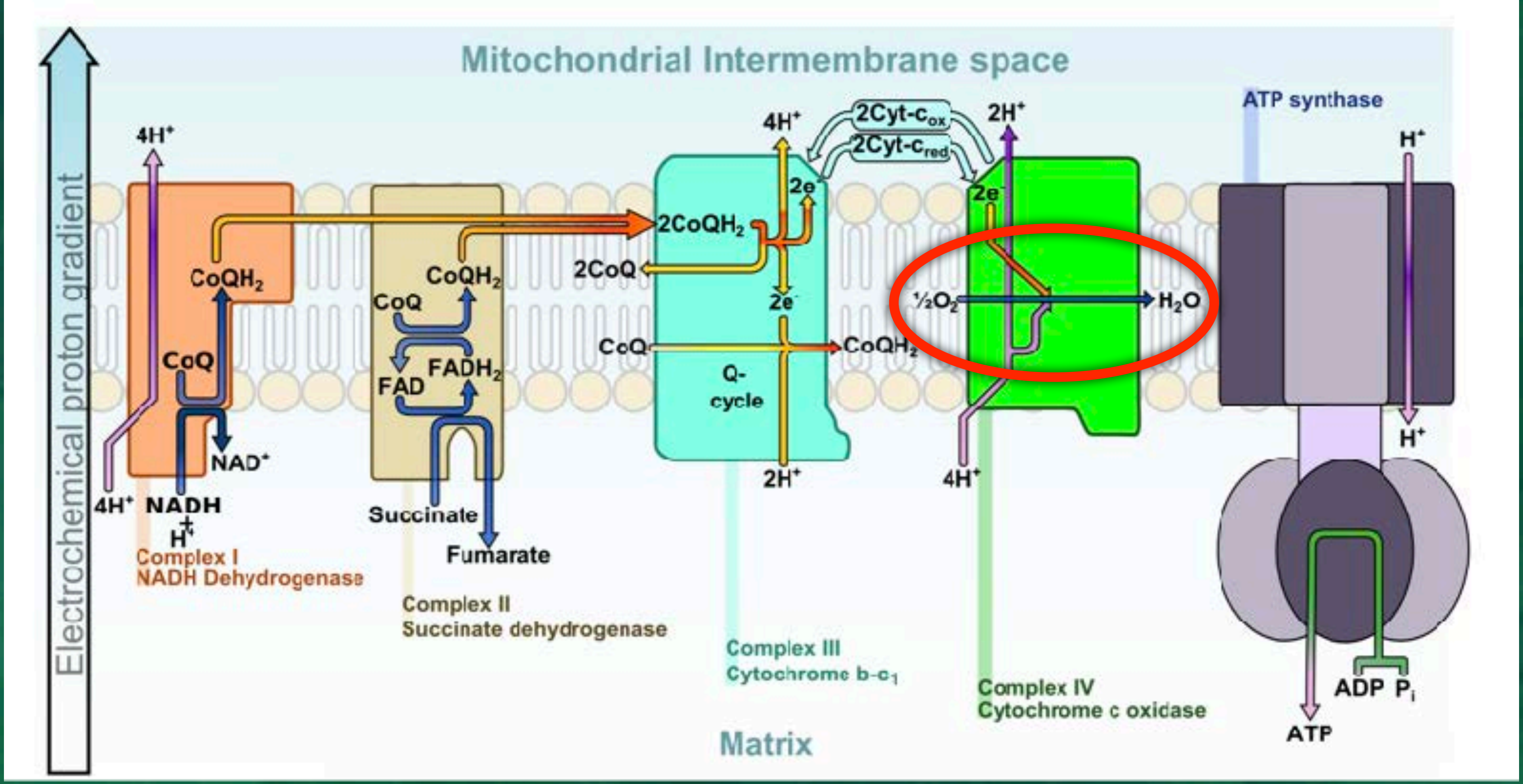

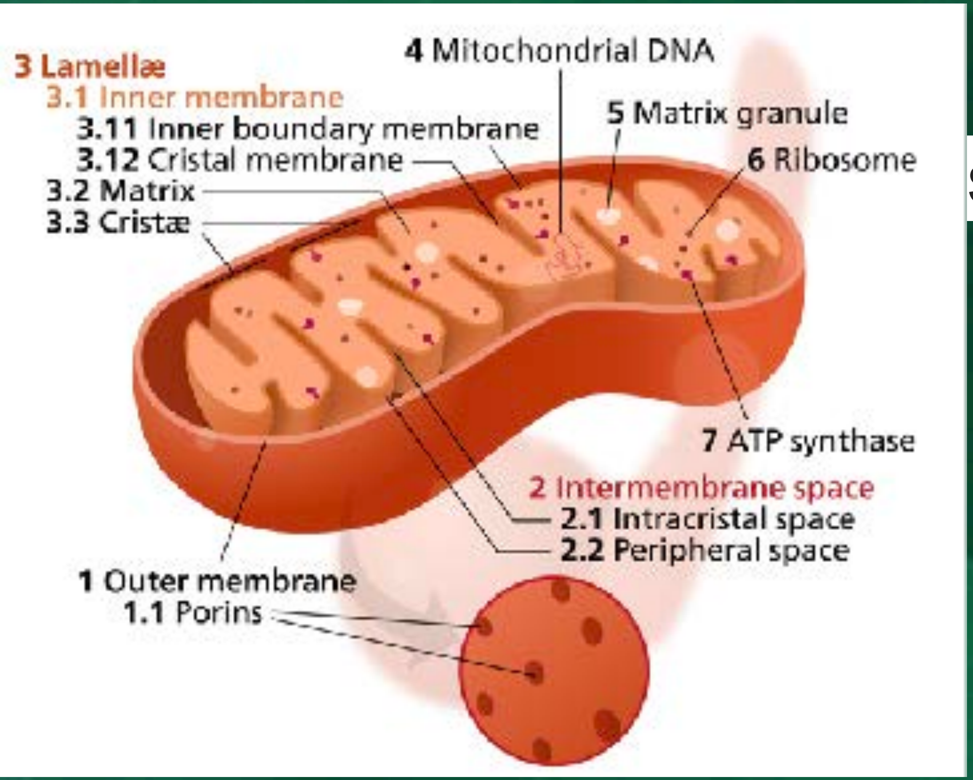

Oxygen is not only required for oxidative phosphorylation but also serves as the essential substrate for the formation of reactive oxygen species

Engulfment of aerobic proteobacteria by primordial anaerobic eukaryotes may have provided protection against the toxicity of increasing oxygen in the primordial atmosphere.

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MAYO CLINIC

April 2021

REVIEW

Check for updates

The Oxygen Cascade During Exercise in Health and Disease

Paolo B. Dominelli, PhD; Chad C. Wiggins, PhD; Tuhin K. Roy, PhD, MD; Timothy W. Secomb, PhD; Timothy B. Curry, PhD, MD; and Michael J. Joyner, MD

Abstract

The oxygen transport cascade describes the physiological steps that bring atmospheric oxygen into the body where it is delivered and consumed by metabolically active tissue. As such, the oxygen cascade is fundamental to our understanding of exercise in health and disease. Our narrative review will highlight each step of the oxygen transport cascade from inspiration of atmospheric oxygen down to mitochondrial consumption in both healthy active males and females along with clinical conditions. We will focus on how different steps interact along with principles of homeostasis, physiological redundancies, and adaptation. In particular, we highlight some of the parallels between elite athletes and clinical conditions in terms of the oxygen cascade.

 ■ Mayo Clin Proc. 2021;96(4):1017-1032

In the era of molecular biology it is easy to overlook the central role that the oxygen molecule plays in life. In complex organisms, where most cells are anatomically remote from atmospheric oxygen, a transport and gas exchange system is required to move oxygen from the air to the tissues and supports the continuous generation of adenosine triphosphate via oxidative metabolism. To defend whole body homeostasis, this system must be robust enough to sustain vast increases in oxidative metabolism during exercise, survive at high altitude, and — at the opposite end of the homeostatic spectrum — withstand substantial insults to key elements of the system associated with disease. In this review, we will follow the movement of oxygen from the air to the tissues and use examples ranging from elite athletes, rare patients, and comparative biology to show key principles of oxygen transport in humans. The impressive adaptive nature of the cardiopulmonary system will be emphasized and the redundant nature of physiological control mechanisms and related anatomical design features will be highlighted.

THE PROBLEM

The partial pressure of oxygen in air at sea level is ~150 mm Hg, but in the mitochondria of exercising skeletal muscle the partial pressure of oxygen can be ~100-fold lower without significant engagement of anaerobic energy metabolism. Thus, the question is, how does this happen and what systems are engaged as it occurs? In this context, it is also important to consider the range of oxygen consumption that can be seen in humans. In healthy young adults, resting metabolic rate is approximately 3.5 mL $O_2 \cdot kg^{-1}$ of body weight $\cdot$ min^{-1} and it can increase to more than 90 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$ in at least some of the most aerobically trained elite athletes.[1] At the opposite end of the O_2 uptake spectrum, even modest metabolic rates require physiological redundancies to be engaged in patients with diseases that hinder the ability to take up, transfer, and utilize oxygen. Notable examples include marked tachypnea or tachycardia even during very modest levels of exercise in patients with diseases, such as chronic obstructive pulmonary disease or congestive heart failure, along with a marked redistribution of blood flow away from inactive tissues to the active muscles.[2]

From the Department of Kinesiology, University of Waterloo, Ontario, Canada (P.B.D.); Department of Anesthesiology and Perioperative Medicine, Mayo Clinic, Rochester, MN (C.C.W., T.K.R., T.B.C., M.J.J.); and the Departments of Physiology and Mathematics, University of Arizona, Tucson (T.W.S.).

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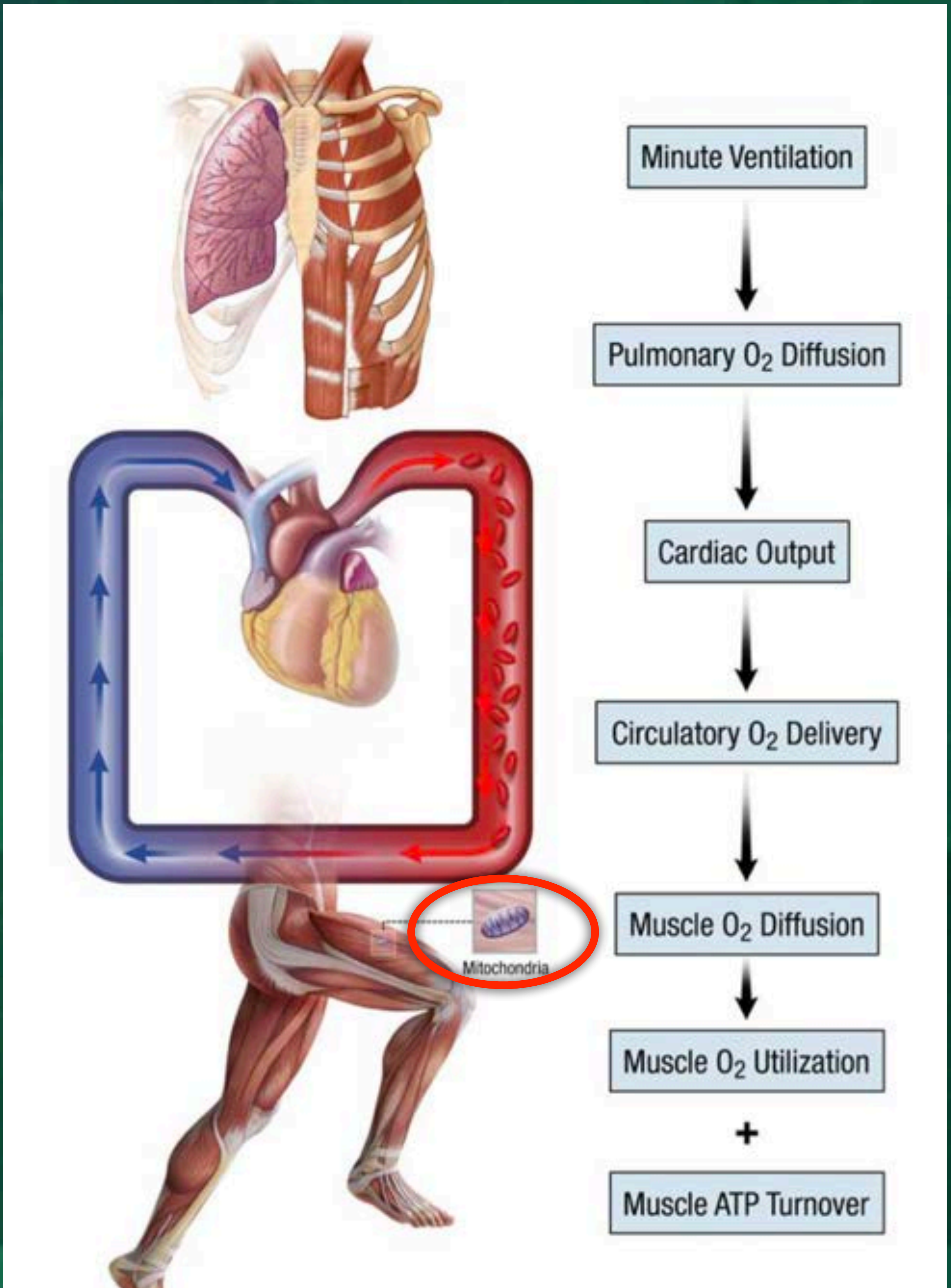

The Oxygen Cascade During Exercise in Health and Disease
Mayo Clin Proc. 2021 April; 96(4): 1017–1032.

MAYO CLINIC

REVIEW

The Oxygen Cascade During Exercise in Health and Disease

Check for updates

- **The partial pressure of oxygen in air at sea level is ~150 mmHg but *in the mitochondria of exercising skeletal muscle* the partial pressure of oxygen can be ~100-fold lower without significant engagement of anaerobic energy metabolism.**

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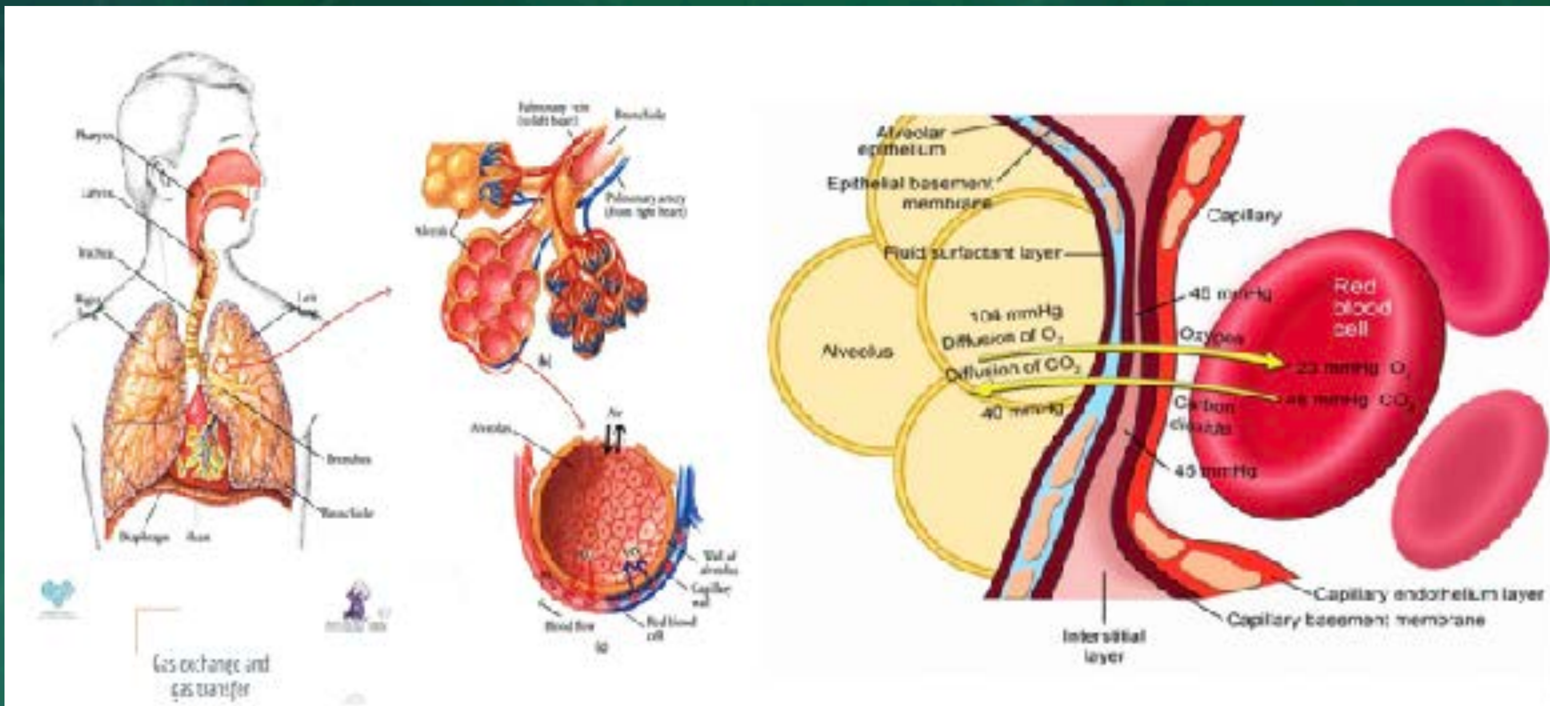
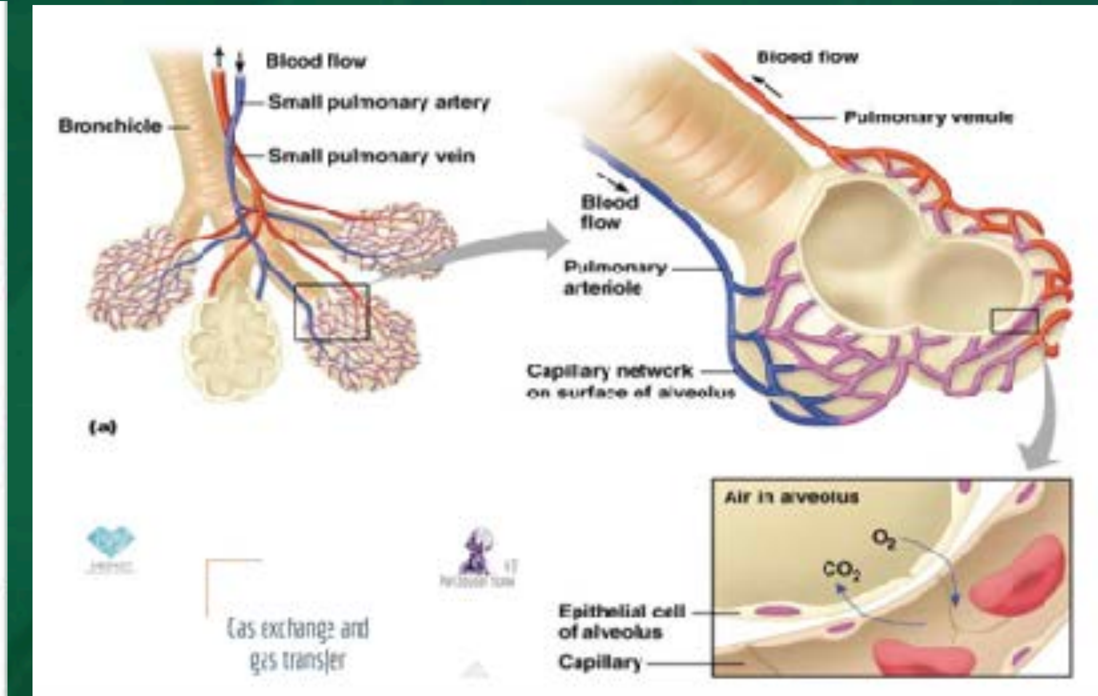
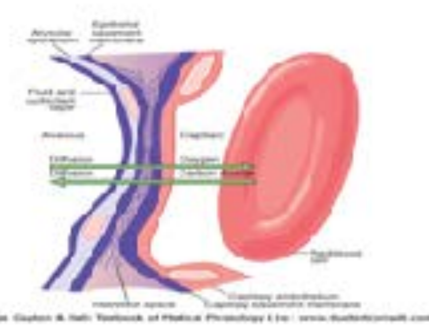




LAYERS OF THE RESPIRATORY MEMBRANE

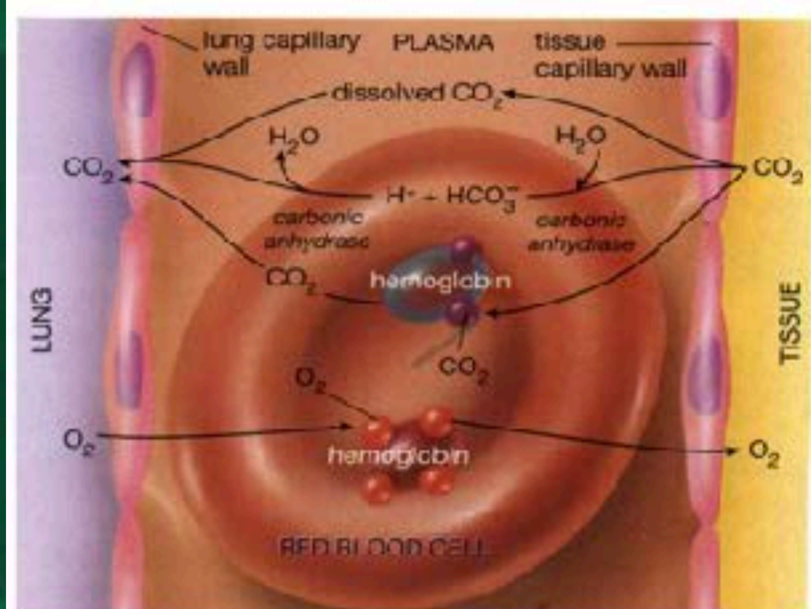
Diffusion of oxygen from the alveolus into the red blood cell and diffusion of carbon dioxide in the opposite direction. Note the following different layers of the respiratory membrane:

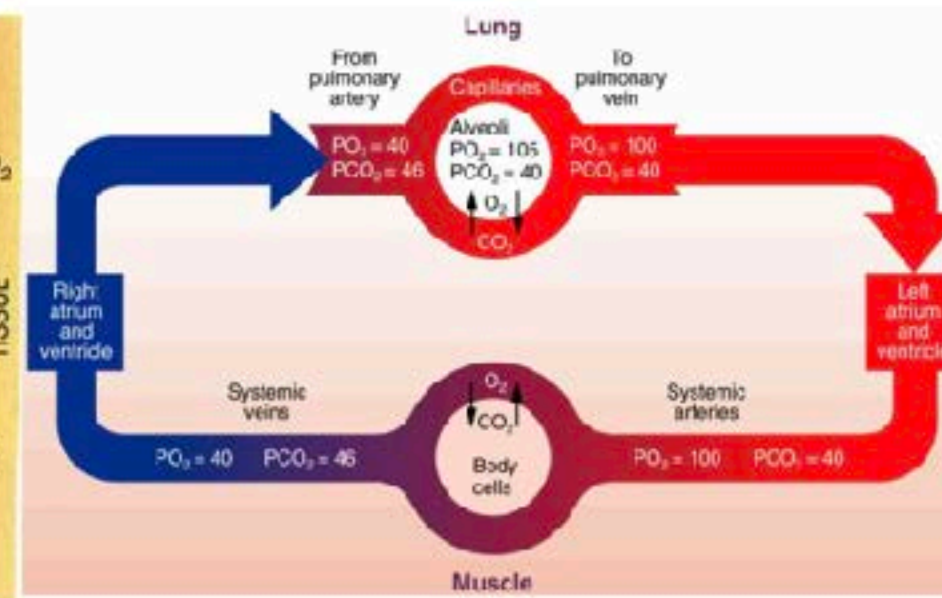
1. A layer of fluid lining the alveous
2. The alveolar epithelium
3. An epithelial basement membrane
4. Interstitial space
5. Capillary basement membrane
6. The capillary endothelial membrane



Partial pressure of gases

Gas exchange and gas transfer





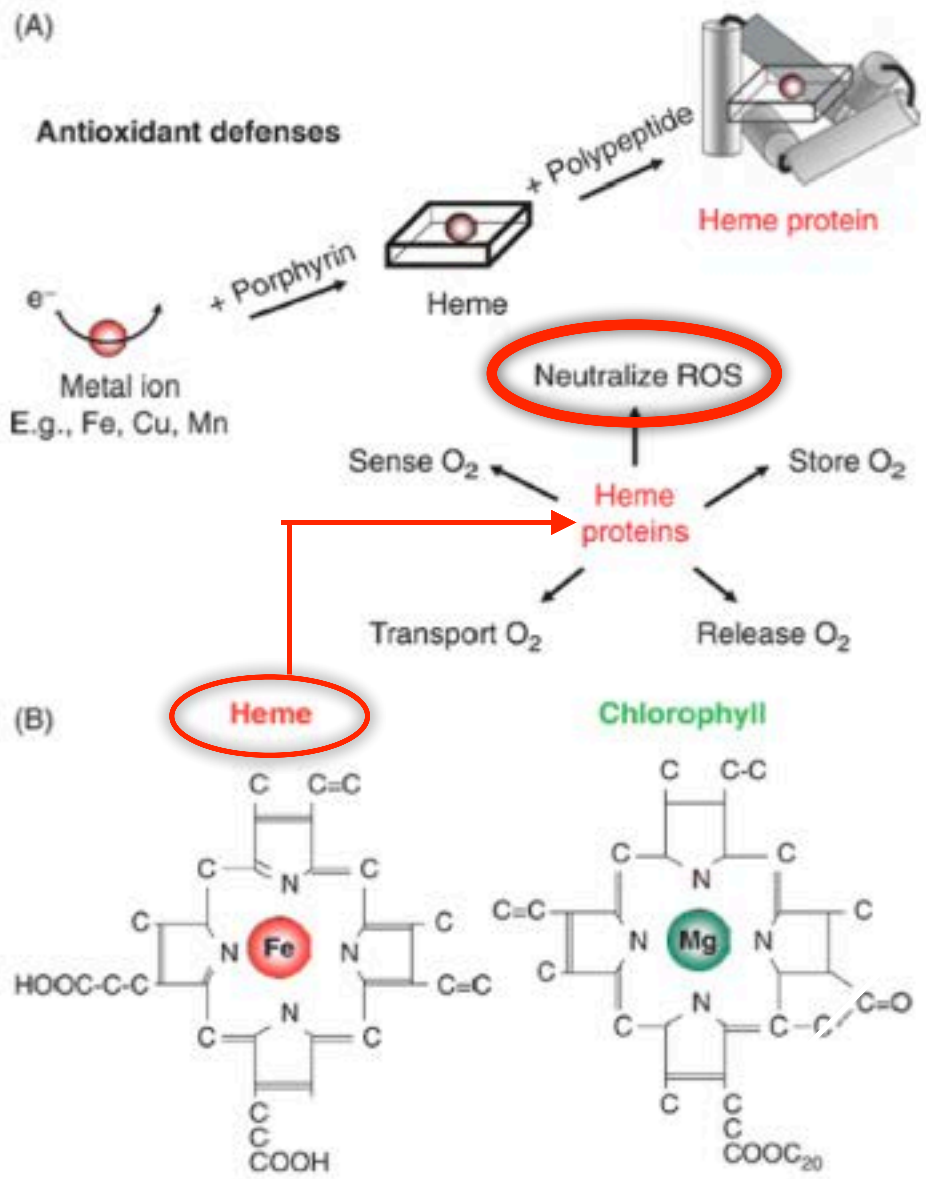


Figure 2.
(A) Transitional metals ions functioned as signaling and antioxidant molecules in the earliest organisms. A molecular cage, for example, prophyrin ring, trapped these metal ions, for example, forming a heme molecule. Adding various polypeptides modulated the action of heme, resulting in heme proteins. By exaptation heme proteins participated in the neutralization of reactive O_2 species as well as the sensing, storage, transport, and release of O_2. (B) Structure of heme (containing iron) is remarkably similar to that of chlorophyll (containing magnesium).

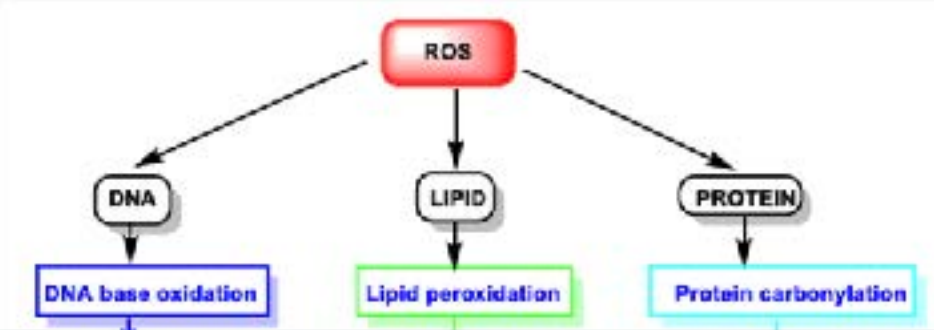
Reactive oxygen species (ROS)

are highly reactive chemicals formed from diatomic oxygen (O_2).

Examples of ROS:

peroxides, superoxide, hydroxyl radical, singlet oxygen, and alpha-oxygen.

ROS action on DNA, lipids and proteins lead to DNA base oxidation, lipid peroxidation and protein carbonylation, respectively. * Unpaired electron.



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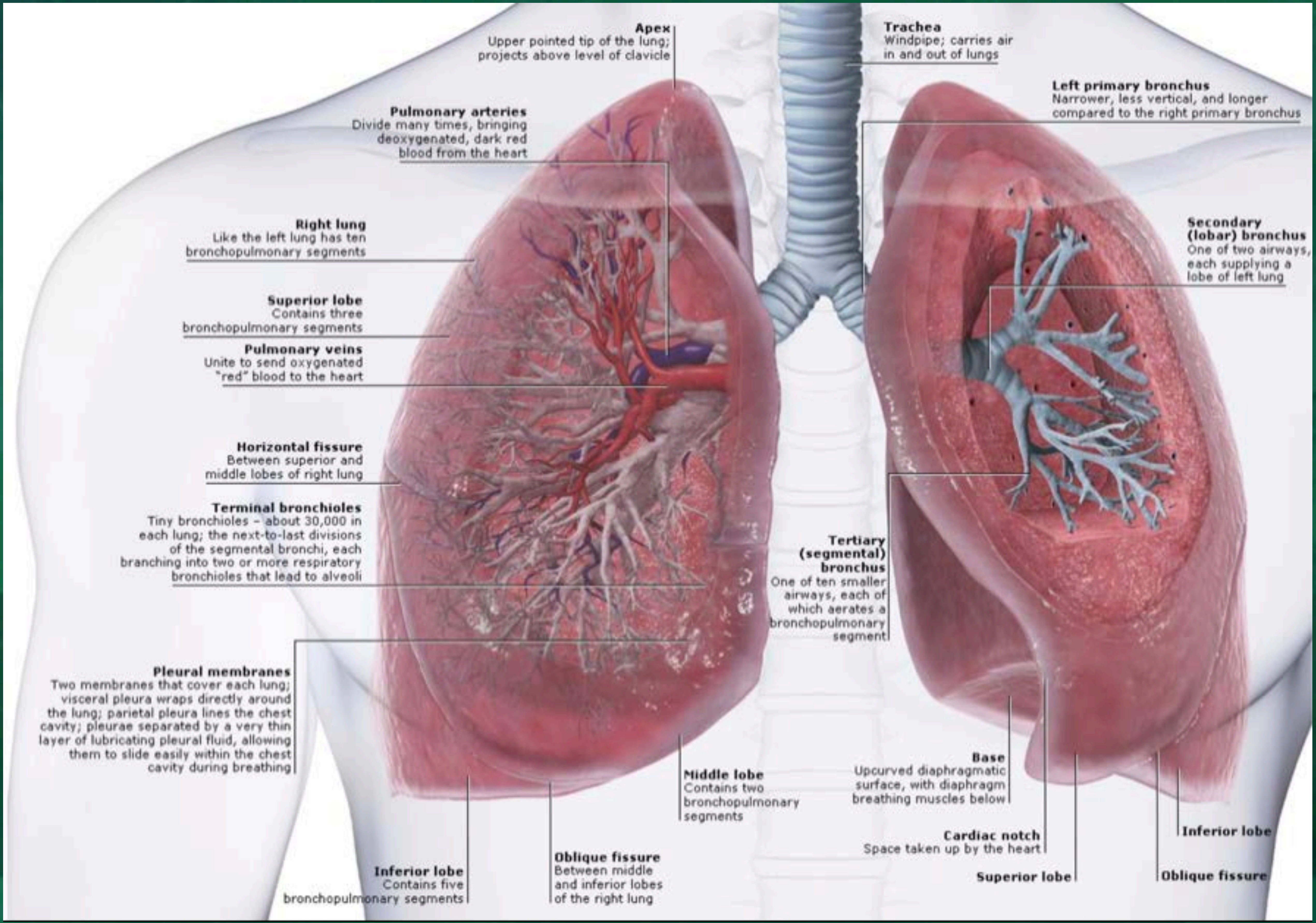
What will be covered:

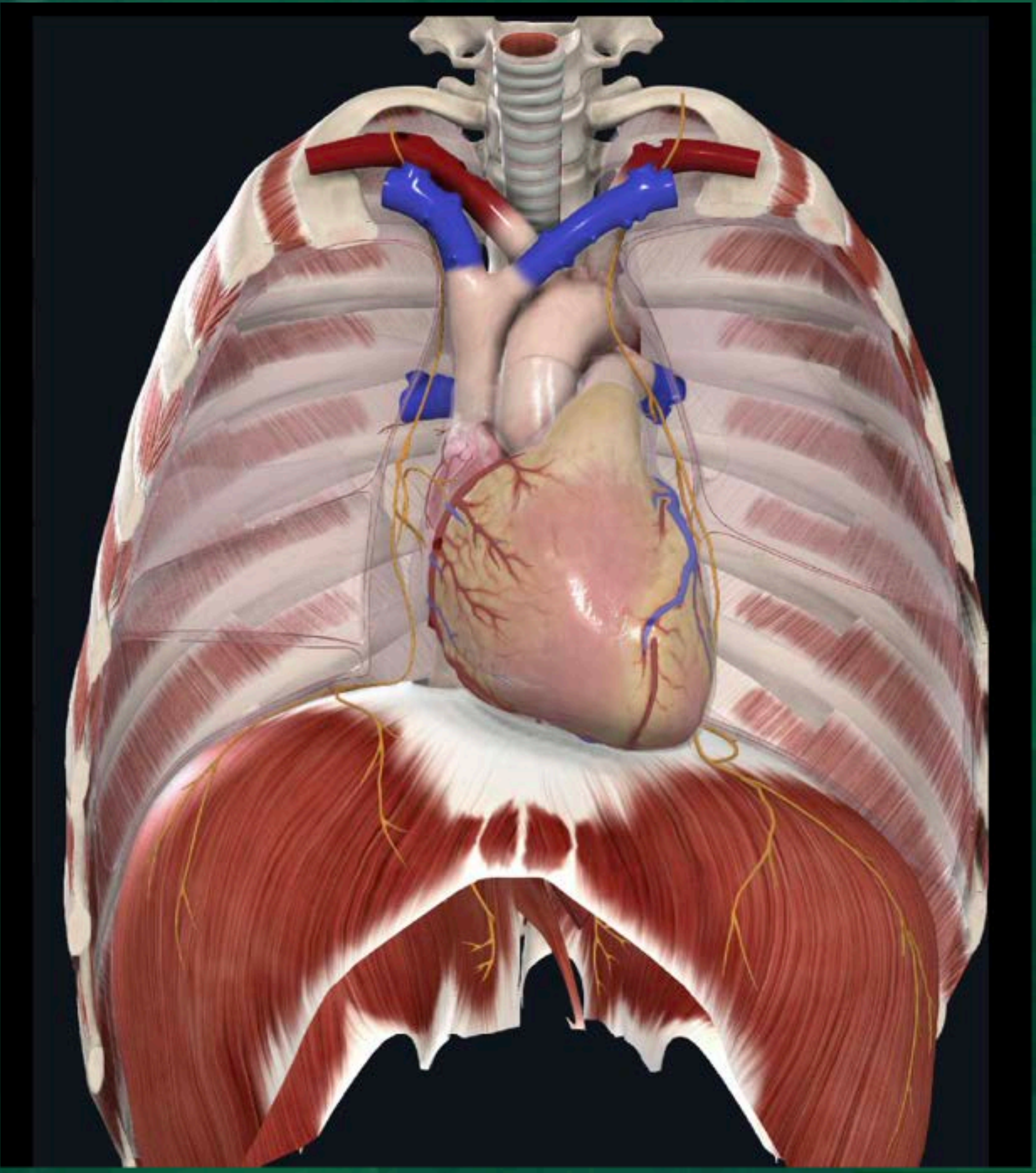
1) How *elemental* Iron (Fe) and Oxygen (O) got their start

2) How *molecular* O_2 in oceans and atmosphere rose long after life began … how Fe^{2+} delayed that rise

3) Why Iron (Fe) is central to cellular metabolism

4) Why aerobic (O_2) cellular respiration became dominant in a previously anaerobic world


Apex
Upper pointed tip of the lung; projects above level of clavicle
Trachea
Windpipe; carries air in and out of lungs
Pulmonary arteries
Divide many times, bringing deoxygenated, dark red blood from the heart
Left primary bronchus
Narrower, less vertical, and longer compared to the right primary bronchus
Right lung
Like the left lung has ten bronchopulmonary segments
Secondary (lobar) bronchus
One of two airways, each supplying a lobe of left lung
Superior lobe
Contains three bronchopulmonary segments
Pulmonary veins
Unite to send oxygenated "red" blood to the heart
Horizontal fissure
Between superior and middle lobes of right lung
Terminal bronchioles
Tiny bronchioles – about 30,000 in each lung; the next-to-last divisions of the segmental bronchi, each branching into two or more respiratory bronchioles that lead to alveoli
Tertiary (segmental) bronchus
One of ten smaller airways, each of which aerates a bronchopulmonary segment
Pleural membranes
Two membranes that cover each lung; visceral pleura wraps directly around the lung; parietal pleura lines the chest cavity; pleurae separated by a very thin layer of lubricating pleural fluid, allowing them to slide easily within the chest cavity during breathing
Middle lobe
Contains two bronchopulmonary segments
Base
Upcurved diaphragmatic surface, with diaphragm breathing muscles below
Inferior lobe
Cardiac notch
Space taken up by the heart
Oblique fissure
Between middle and inferior lobes of the right lung
Inferior lobe
Contains five bronchopulmonary segments
Superior lobe
Oblique fissure


Complete Anatomy 2023
3D4MEDICAL

What you see depends on your perspective.

NASA EARTH'S MOON

near

far

Tidal Locking - **You've only ever seen half of the Moon in the sky. Earth's Moon rotates, but it takes precisely as long for the Moon to spin on its axis as it does to complete its monthly orbit around Earth. As a result, the Moon never turns its back to us. In fact, all the solar system's large moons are tidally locked with their planets.**

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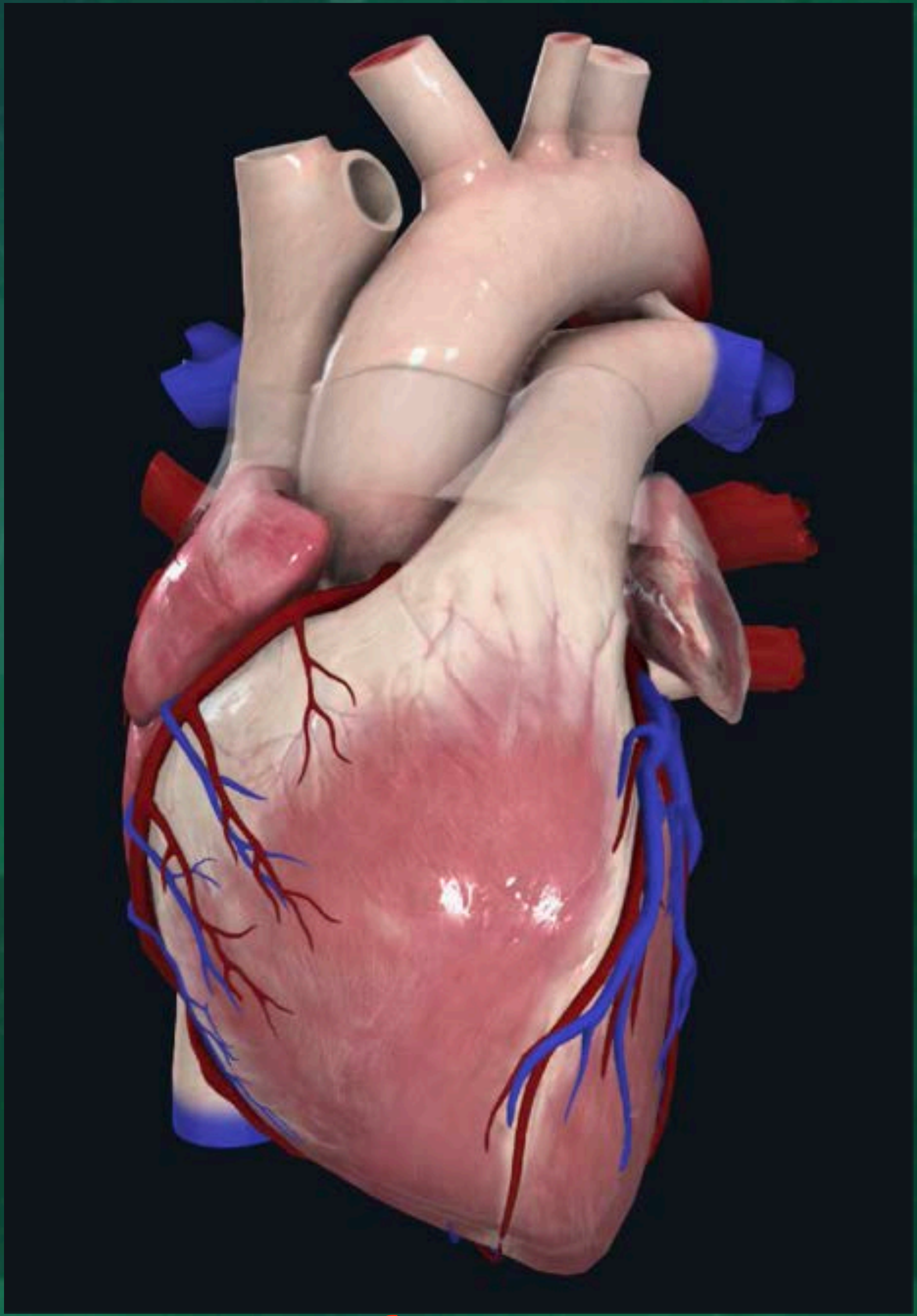
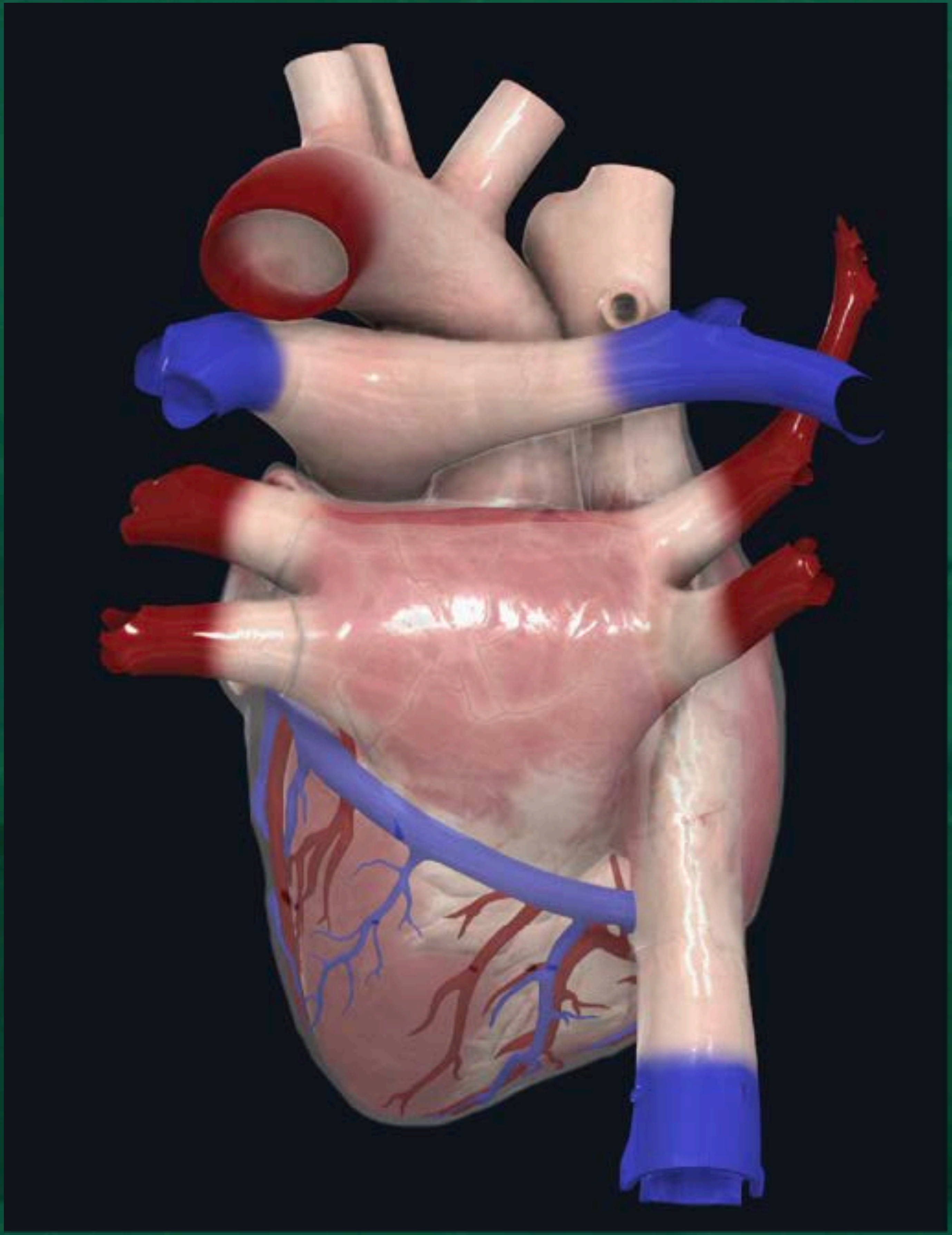


front



back

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We shall not cease from exploration

And the end of all our exploring

Will be to arrive where we started

And know the place for the first time.

T.S. Eliot --- "Little Gidding" ... *Four Quartets*

Right there in front of you

... that's where it always is ...

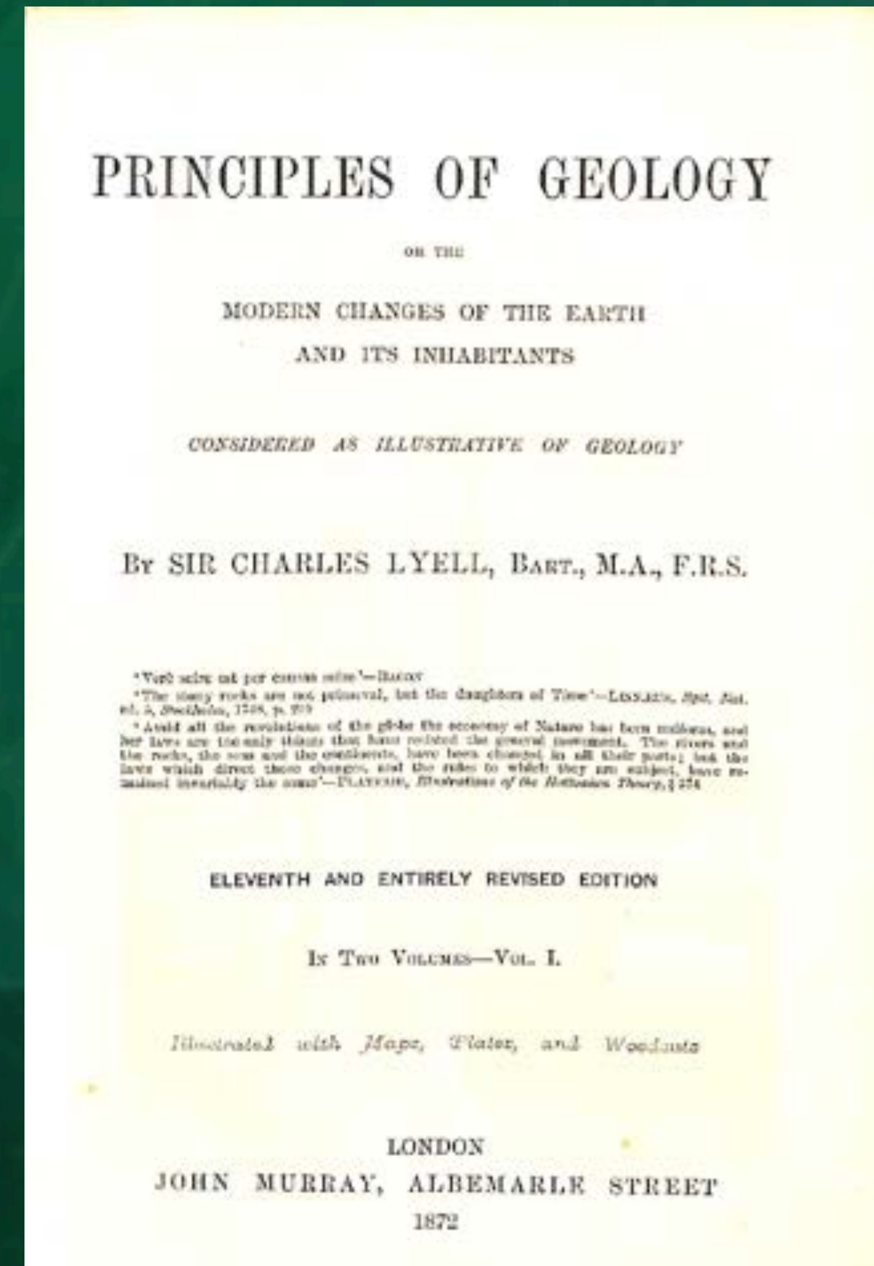
with just a little knowing,

looking becomes seeing,

opening doors into

extraordinary worlds

imagessays.com -> ****seeing****



PRINCIPLES OF GEOLOGY

OR THE

MODERN CHANGES OF THE EARTH
AND ITS INHABITANTS

CONSIDERED AS ILLUSTRATIVE OF GEOLOGY

BY SIR CHARLES LYELL, BART., M.A., F.R.S.

ELEVENTH AND ENTIRELY REVISED EDITION

IN TWO VOLUMES—VOL. I.

Illustrated with Maps, Plates, and Woodcuts

LONDON
JOHN MURRAY, ALBEMARLE STREET
1872

"From the abundance, accessibility and richness of this iron ore, its proximity to the coal field and to the navigation of the Tombigbee River, I can hardly doubt that, like the coal itself, [Birmingham] is destined, at no distant day, to be a source of great mineral wealth to Alabama." - 1846

Sir Charles Lyell

Principles of Geology - 1830

Within 30 years, Birmingham would spring from the earth at the spot where coal, limestone and iron ore--which gives Red Mountain its color and name -- naturally existed within 20 miles of one another. Birmingham became known as the Magic City because it burst forth from the mountain as if by magic, with 3,086 residents according to the 1880 census.

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Verba volant, scripta manent.

Spoken words fly away, written words remain.

Location of relevant webpages on imagessays.com:

index page

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water	4
ATP	4
adenosine	4
oxygen	3
iron	3
membrane	3
hemoglobin	3
rbc	3
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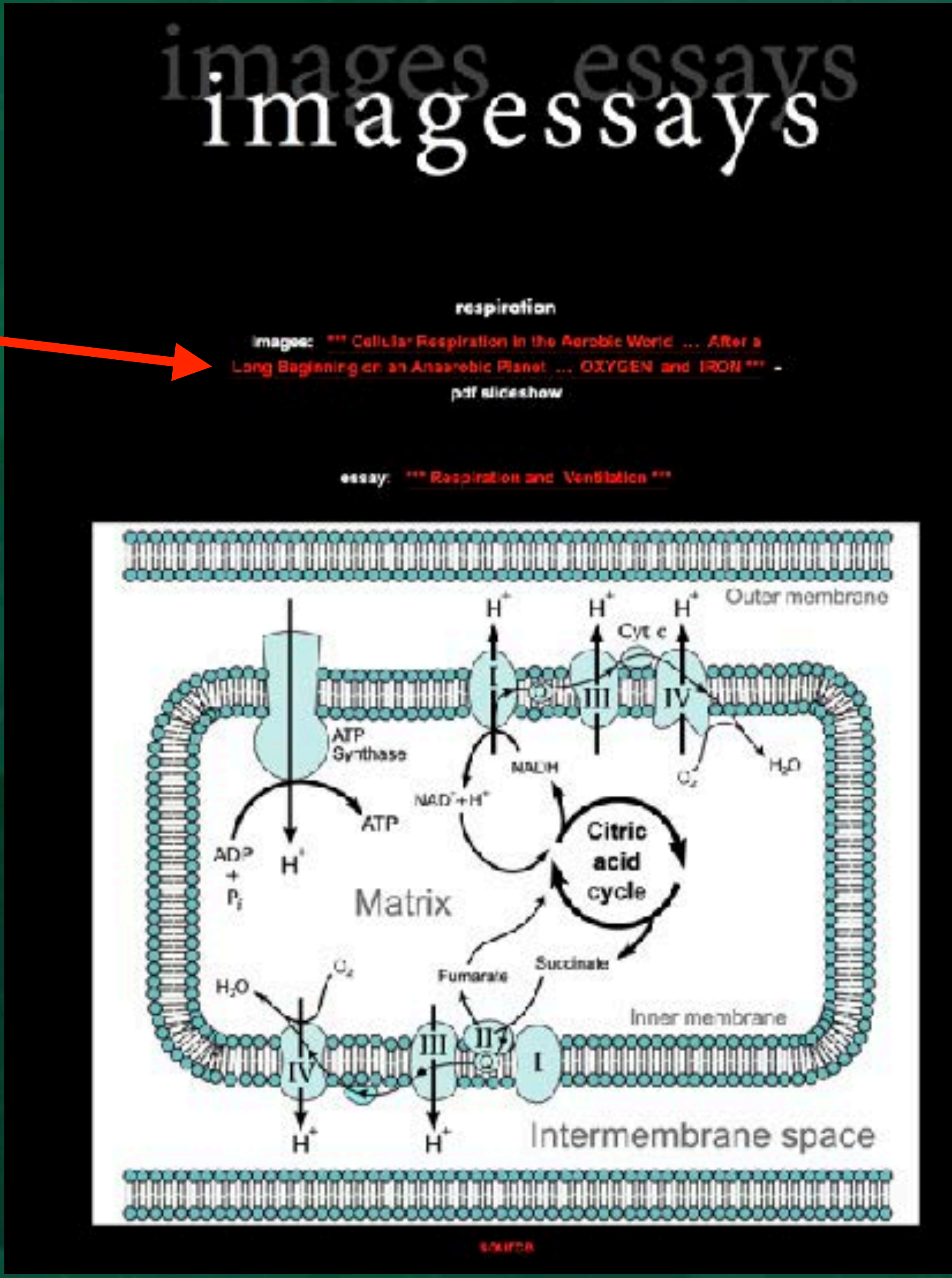
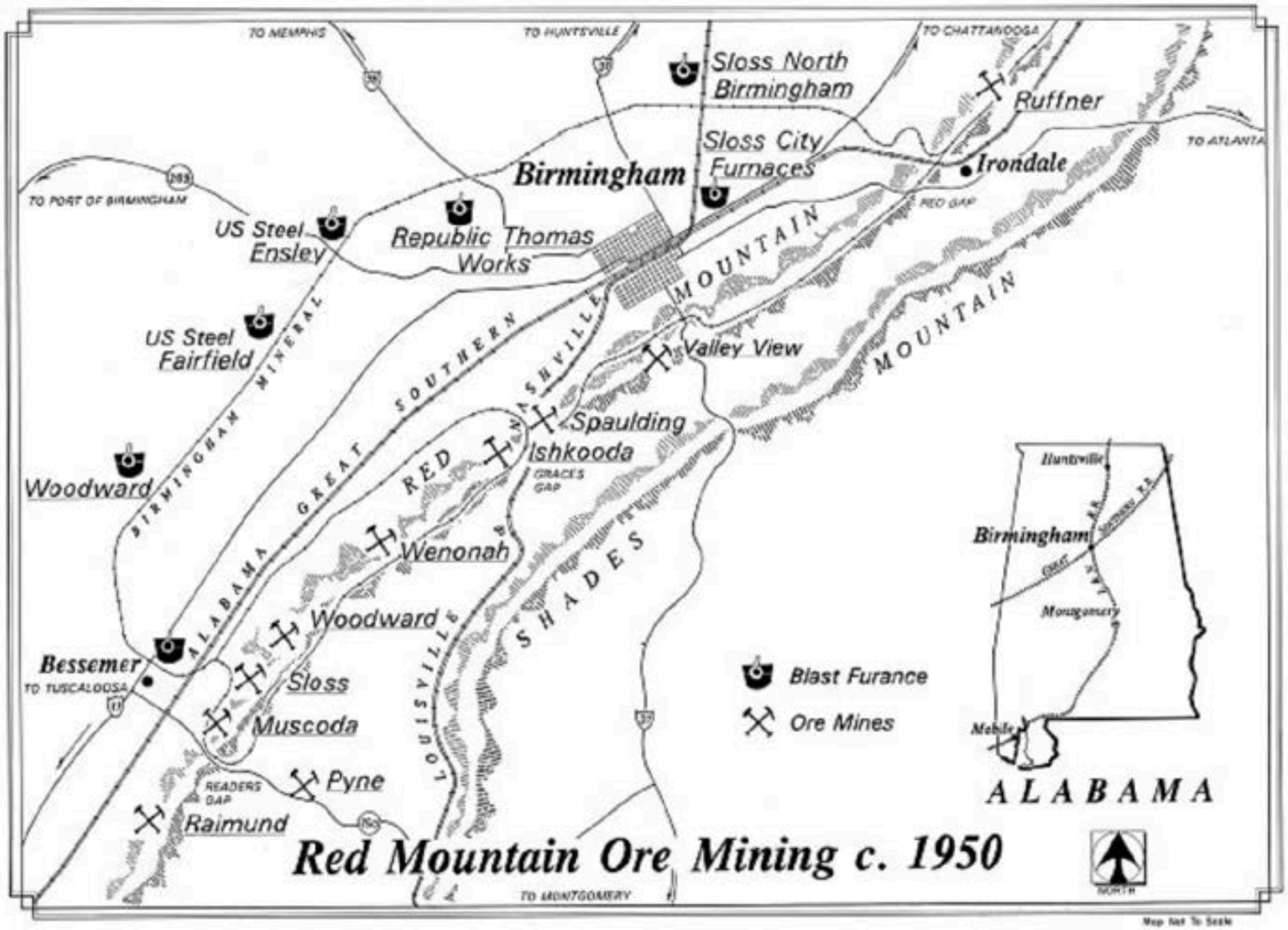
mitochondria	1
stromatolite	1
archaea	1
proton	1




BIRMINGHAM
The
MAGIC
CITY

RED MOUNTAIN MINING OPERATIONS

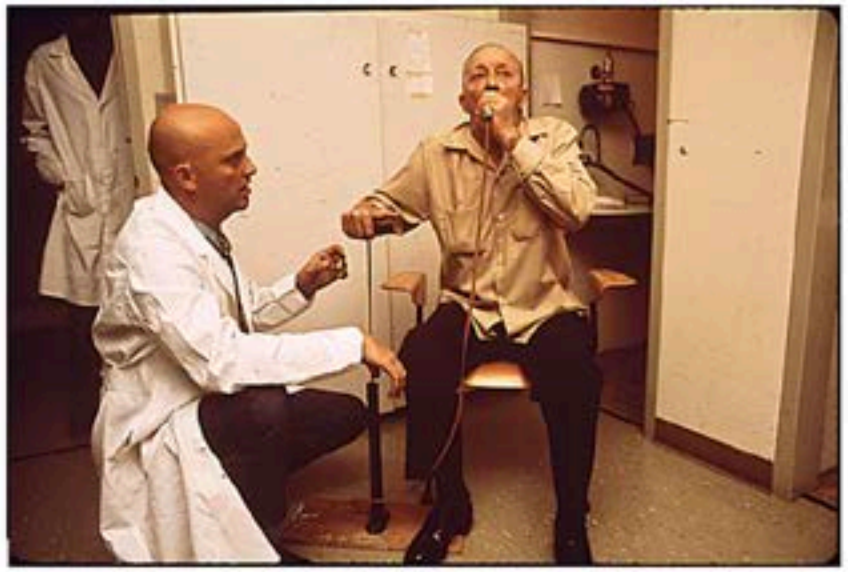
Jefferson County, Alabama



Birmingham: A Powerful History Forged from Iron

The Ensley Works operated between 1888 and 1976 and became part of U.S. Steel in 1907.
For years, it was the largest steel producer in the Southeast.

atlantafed.org



Ben Vaughn Branscomb (1924 – 2016) was a pioneering pulmonologist and distinguished professor emeritus at **UAB**.

He attended the Asheville School and Duke and, due to the need for medical practitioners in World War II, was admitted to medical school there at age 17. After graduating he served briefly on a destroyer during the war. Later, during his internship at the University of Chicago, Branscomb contracted tuberculosis from a patient. He was admitted to the Adirondack Cottage Sanitarium at Saranac Lake, New York.

While there he decided on his specialty and used a full-time job in the sanitarium's research laboratory to begin his training as a pulmonary physiologist. In 1950 he was recalled to military duty in the Korean War before he completed his residency there. He convinced military officials to post him as a researcher for the United States Public Health Service Commissioned Corps, where he pioneered the study of pulmonary function at the National Heart

Once discharged, he was recruited to the **Medical College of Alabama** by **Tinsley Harrison**. Soon after his arrival, Branscomb began setting up pulmonary laboratories at area hospitals equipped to administer the "flow-volume loop" test for breathing capacity that he developed. He became a pioneer of research into emphysema and personally tested 200 members of the 88th United States Congress in July 1963 using a mobile diagnostic unit of his own design. His own research established quantitative links between lung disease and smoking and air pollution.

Branscomb provided critical support to the **Greater Birmingham Alliance to Stop Air Pollution (GASP)** and was the only medical specialist appointed to the Alabama Air Pollution Control Commission in 1971.

Downtown Birmingham December 1966 – photo courtesy of Jefferson County Department of Health

"Smoke City." In the 1960s, that is what truckers used to call Birmingham when they reached the outskirts of Alabama's largest city – the self proclaimed "Pittsburgh of the South."

Before the Clean Air Act was passed in 1970, soot and smog engulfed Birmingham.

GASP

Downtown Street in Birmingham December 1956 – Photo courtesy of the Jefferson County Department of Health

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Oxygen and Iron
are elements
formed by nuclear fusion
in the core of stars

Synthesis of the Elements in Stars*

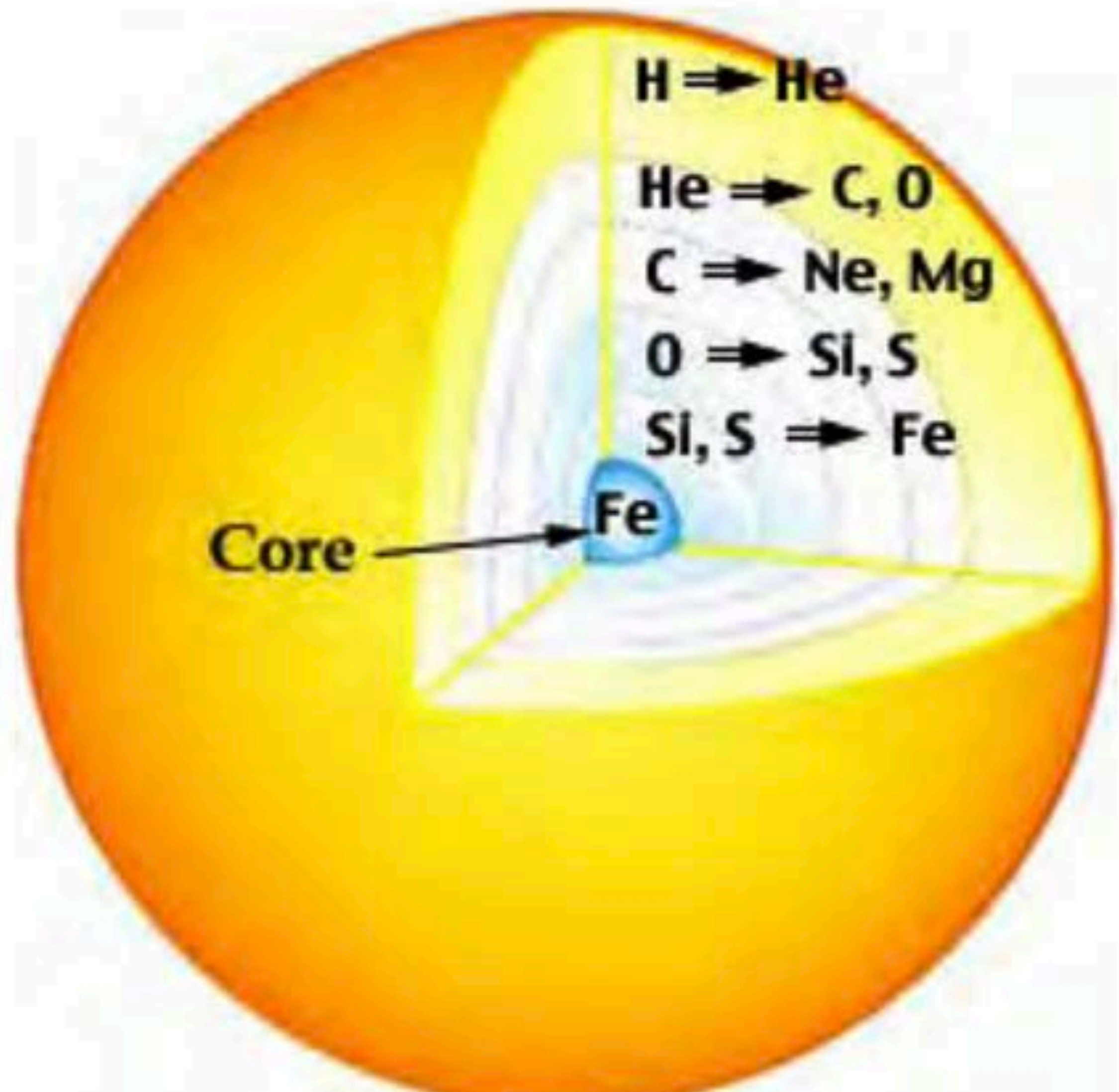
E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

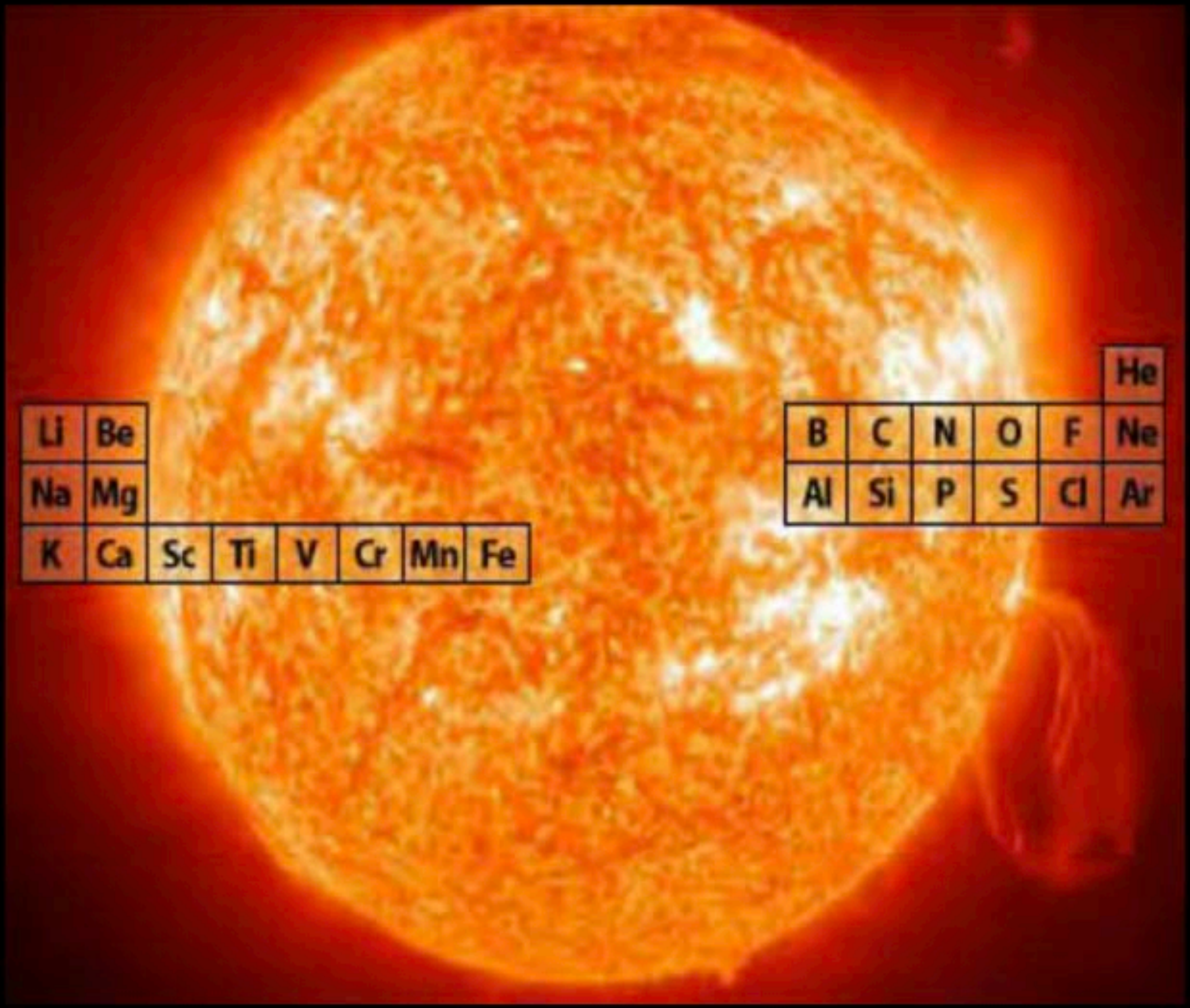
Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)





Stellar nucleosynthesis is the creation (nucleosynthesis) of chemical elements by nuclear fusion reactions within stars. Stellar nucleosynthesis has occurred since the original creation of hydrogen, helium and lithium during the Big Bang. As a predictive theory, it yields accurate estimates of the observed abundances of the elements. It explains why the observed abundances of elements change over time and why some elements and their isotopes are much more abundant than others. The theory was initially proposed by Fred Hoyle in 1946, who later refined it in 1954. Further advances were made, especially to nucleosynthesis by neutron capture of the elements heavier than iron, by Margaret Burbidge, Geoffrey Burbidge, William Alfred Fowler and Hoyle in their famous 1957 B2FH paper, *Synthesis of the Elements in Stars*, which became one of the most heavily cited papers in astrophysics history.

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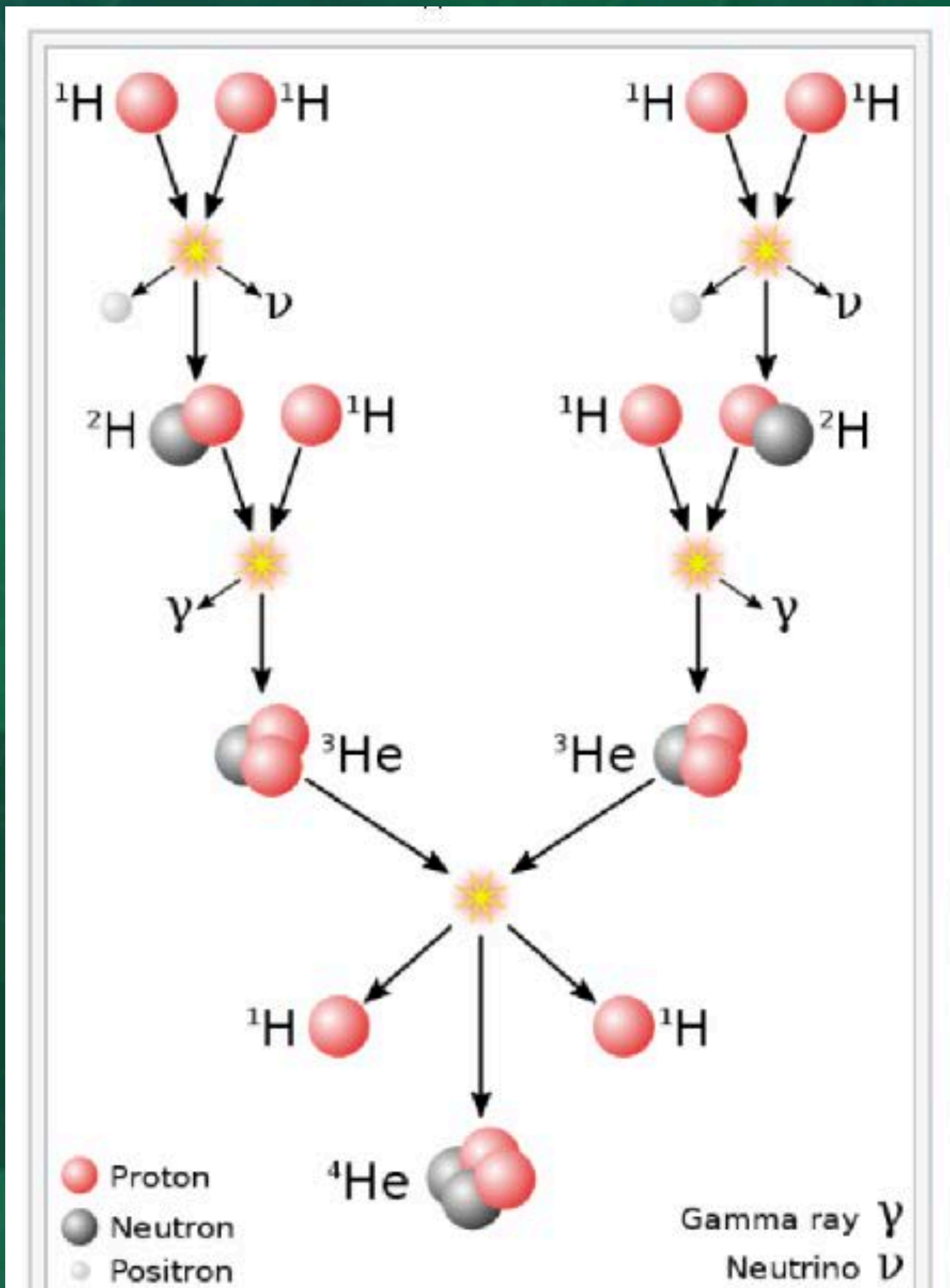
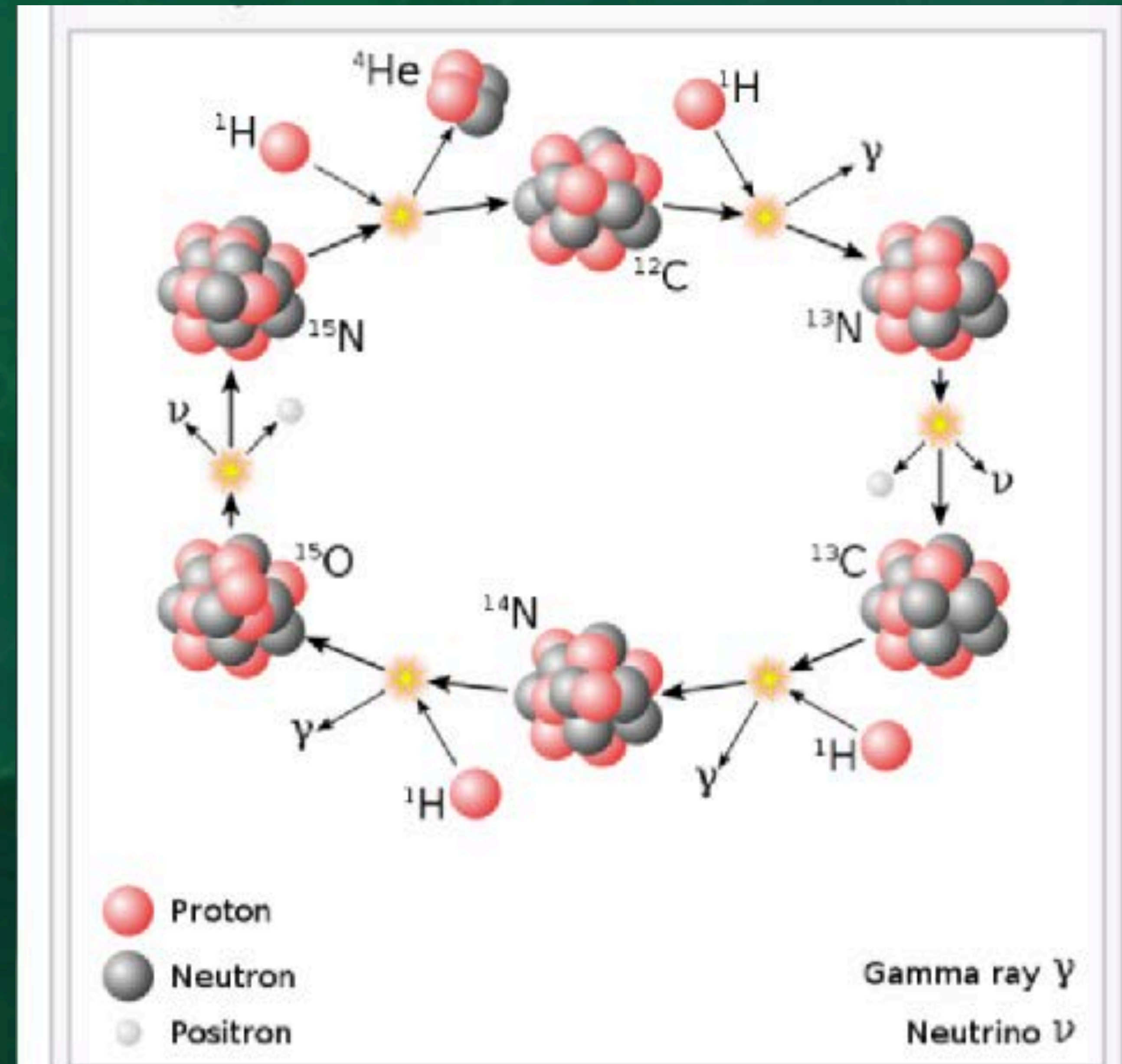
Nuclear fusion **of Hydrogen atoms in the core of stars results in formation of a number of elements, including Oxygen and Iron.**



Proton–proton chain reaction



CNO-I cycle

The helium nucleus is released at the top-left step.

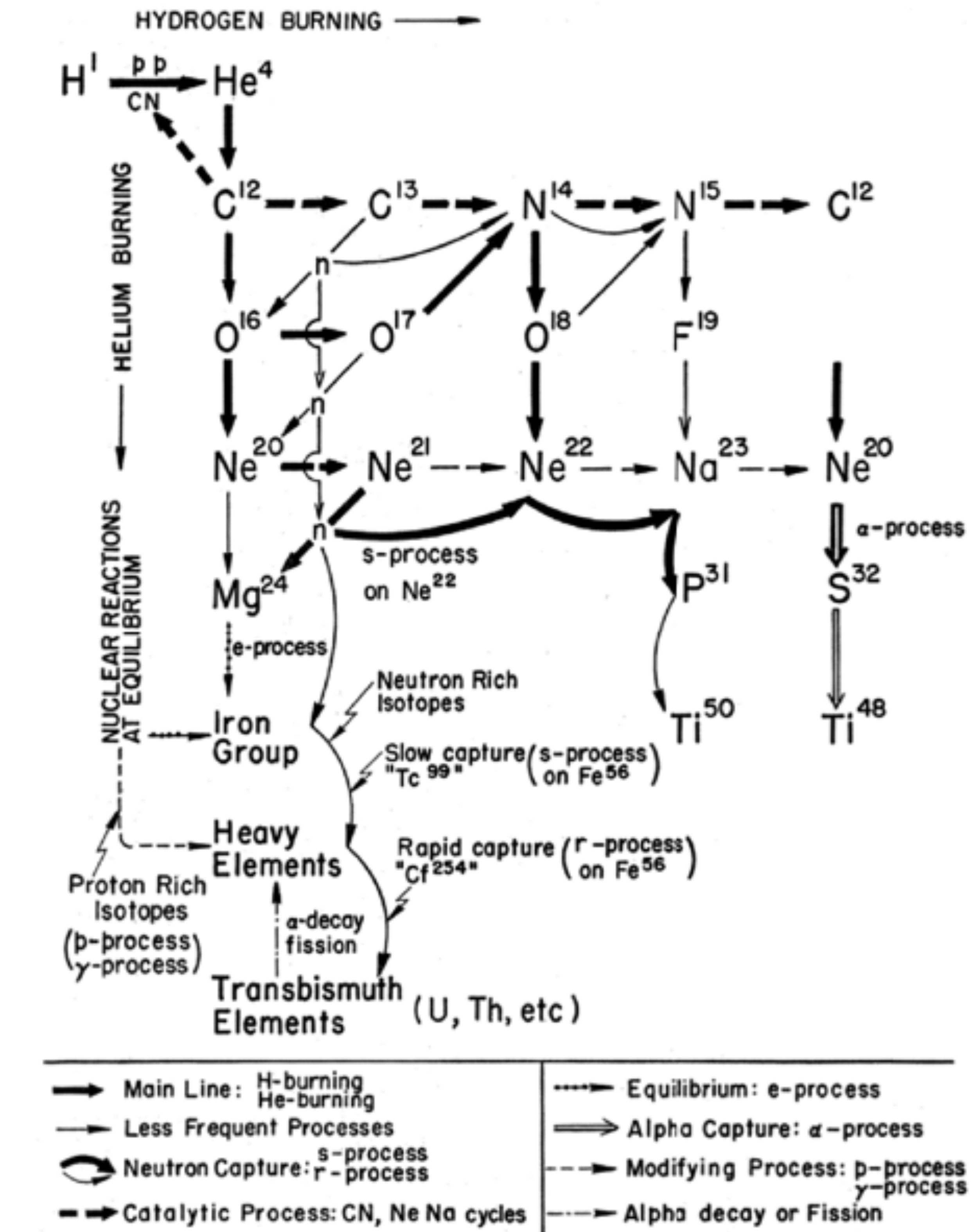


FIG. I,2. A schematic diagram of the nuclear processes by which the synthesis of the elements in stars takes place. Elements synthesized by interactions with protons (hydrogen burning) are listed horizontally. Elements synthesized by interactions with alpha particles (helium burning) and by still more complicated processes are listed vertically. The details of the production of all of the known stable isotopes of carbon, nitrogen, oxygen, fluorine, neon, and sodium are shown completely. Neutron capture

Iron Deficiency

Iron deficiency was an absolute state in the early universe. Large, first-generation stars consume hydrogen and produce helium in their 10 million degree plasma fusion furnace cores. Helium nuclei accumulate, concentrate, fuse, and raise core temperature to 100 million degrees. Further fusion forms beryllium and then carbon. Helium-carbon collisions produce oxygen, then neon, magnesium, and silicon.

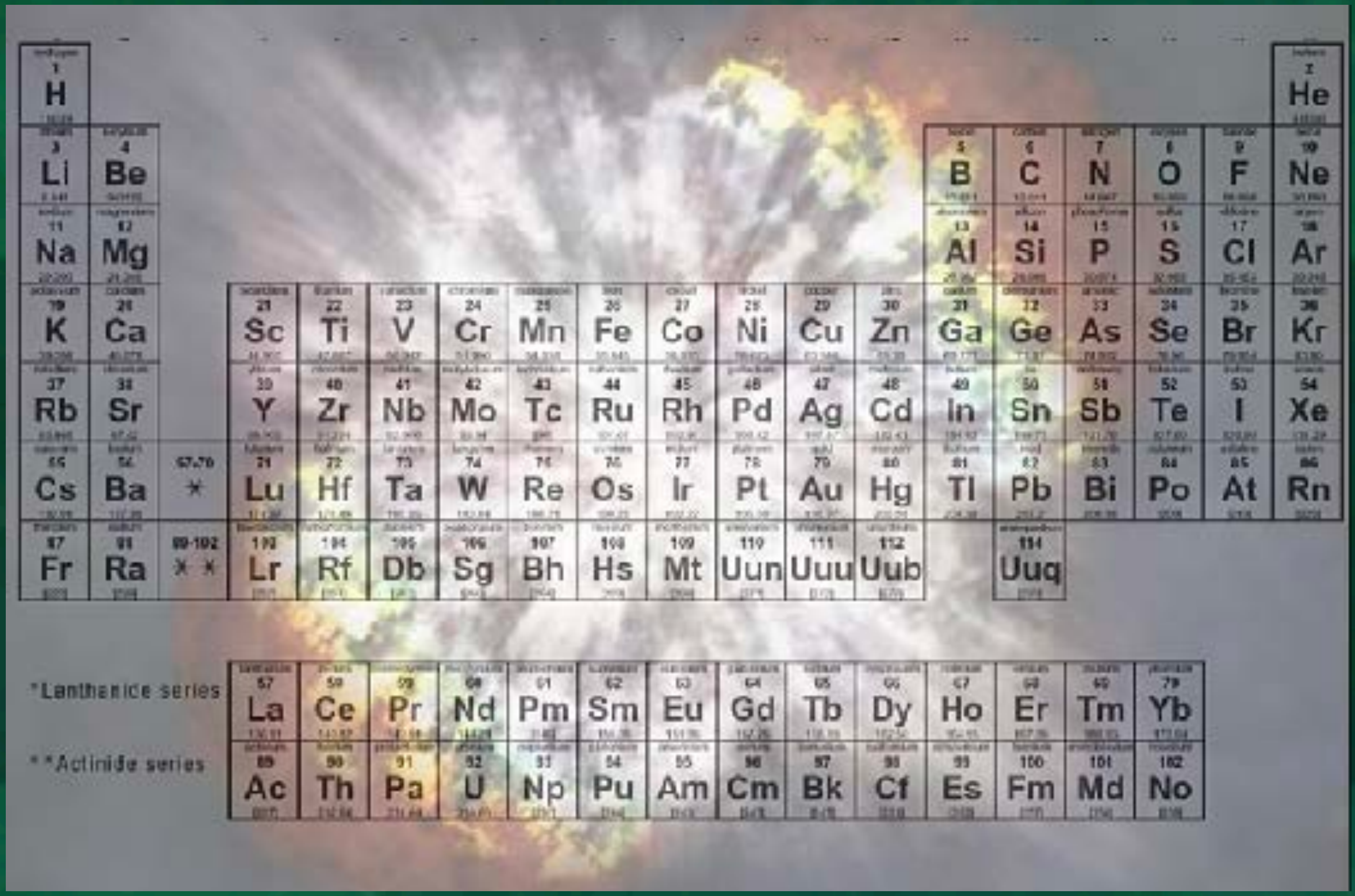
At this point, though, a crisis develops. Although the concentric shells of oxygen, carbon, helium, and hydrogen continue to produce enormous quantities of fusion-derived energy, the accumulating silicon core approaches a thermodynamic dead end. At 4 billion degrees, silicon fusion forges a new element, iron, into existence. The nuclear stability of the rapidly forming iron atoms is greater than that of any other, even more massive, as yet unformed elements that might result from further fusion.

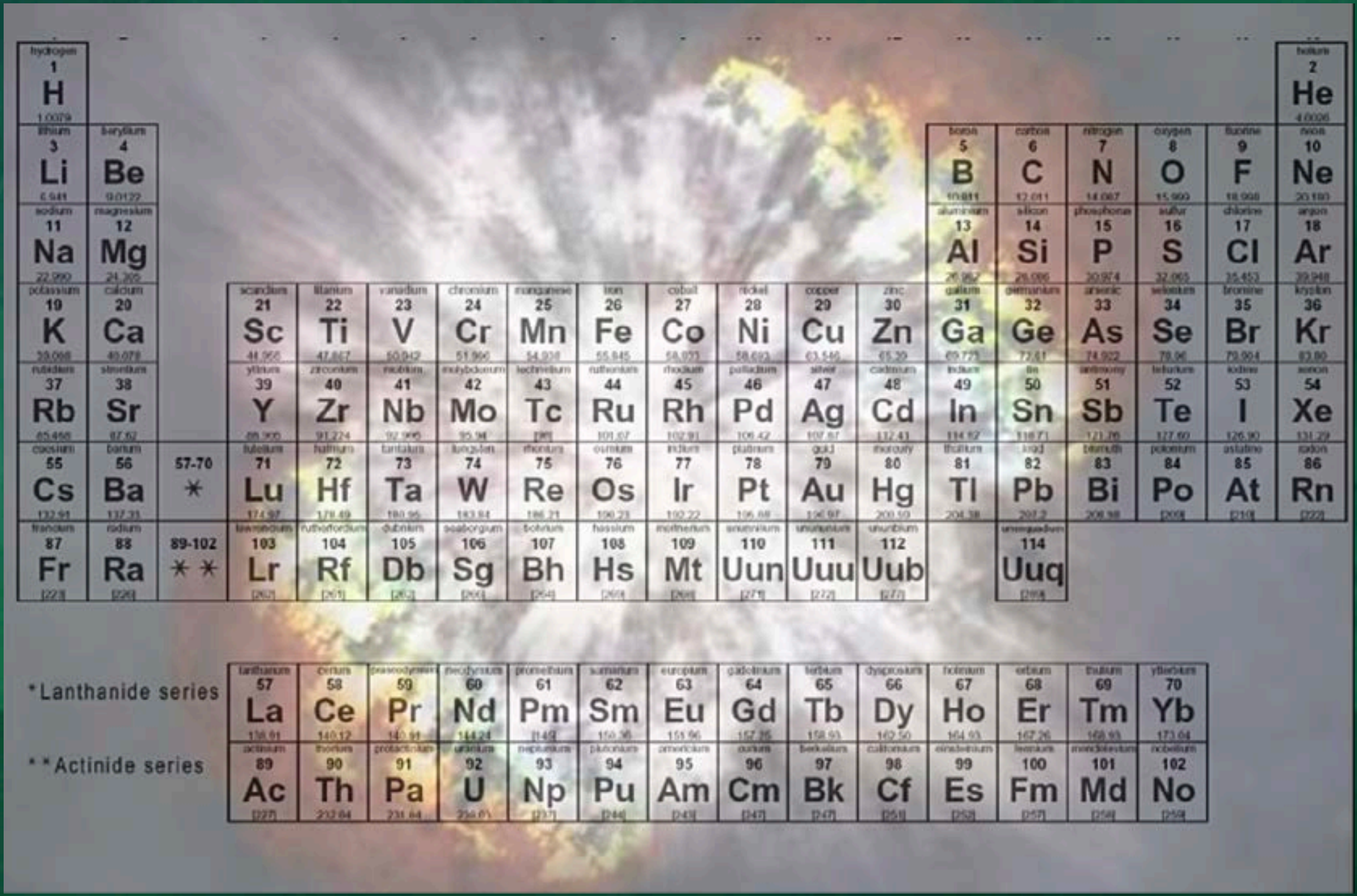
Therefore, iron in the stellar core cannot serve as fuel for exothermic nuclear fusion and provide the immense energy output necessary to heat the core and counterbalance the persistent struggle toward gravitational collapse.

Supernova

As the iron core cools and compresses, the temperature increases. However, iron nuclei are so stable that no further fusion can occur. Instead, iron nuclei succumb to high-energy gamma radiation and photodissociate into helium, triggering a catastrophic collapse under the gravitational pressures of the outer layers. Incredible densities are generated, causing electrons to penetrate protons, forming neutrons and neutrinos. The rebounding shock wave of this collapse accelerates neutrons and neutrinos outward, while the bulk of the core becomes sealed off forever as a new black hole is formed.

The outer layers of the star explode outward at speeds approaching 0.1 c, forming a **supernova**. Neutrons riding the shock wave overtake the exploding layers of silicon, oxygen, carbon, and lighter elemental nuclei. Collision with these elements results in neutron capture and the progressive formation of all the heavier elements.

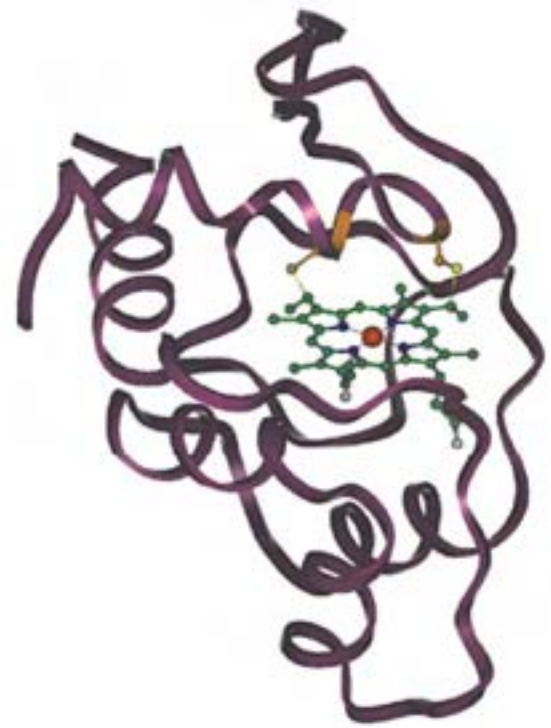




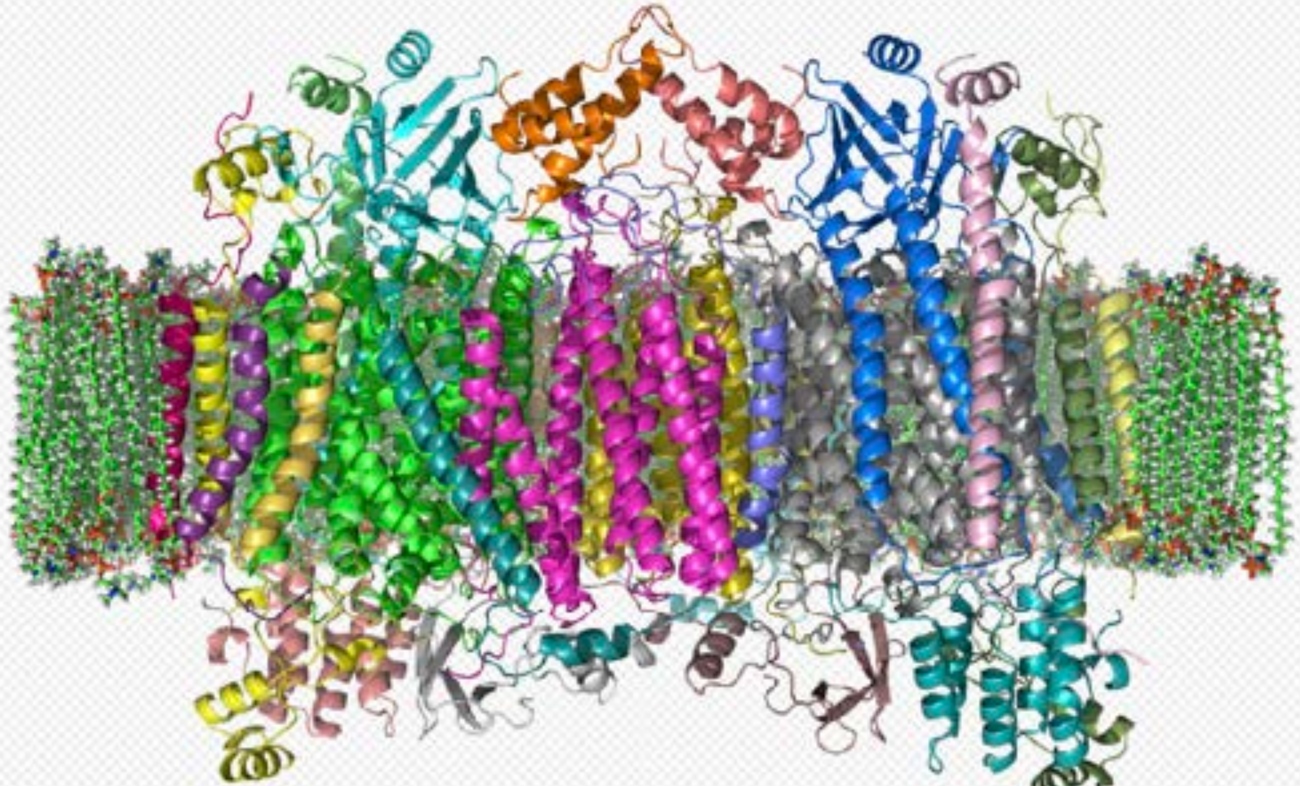
Iron and Oxygen are the most abundant elements on earth: 35% and 30%, respectively.

Most of the iron is concentrated in the planet's core, while the crust contains 6% by mass.

heme



cytochrome



cytochrome c oxidase in membrane

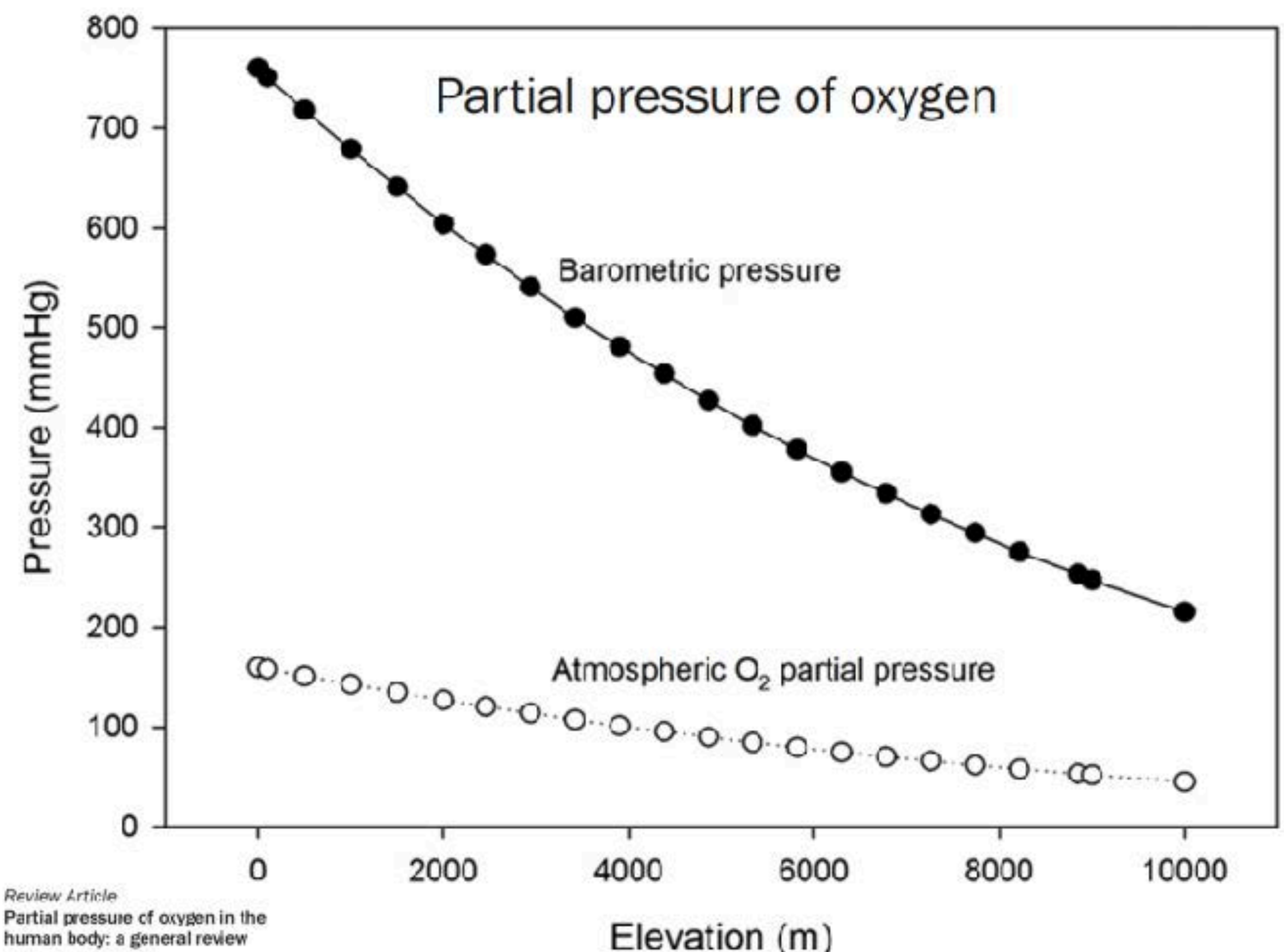
Regarding the composition of the atmosphere:

1) Earth's atmosphere is not the same in every location on the planet.

(*3rd dimension: altitude*)

2) Earth's atmosphere has not been the same throughout the history of the planet.

(*4th dimension: time*)



Review Article
Partial pressure of oxygen in the human body: a general review
Am J Blood Res 2019;9(1):1-14

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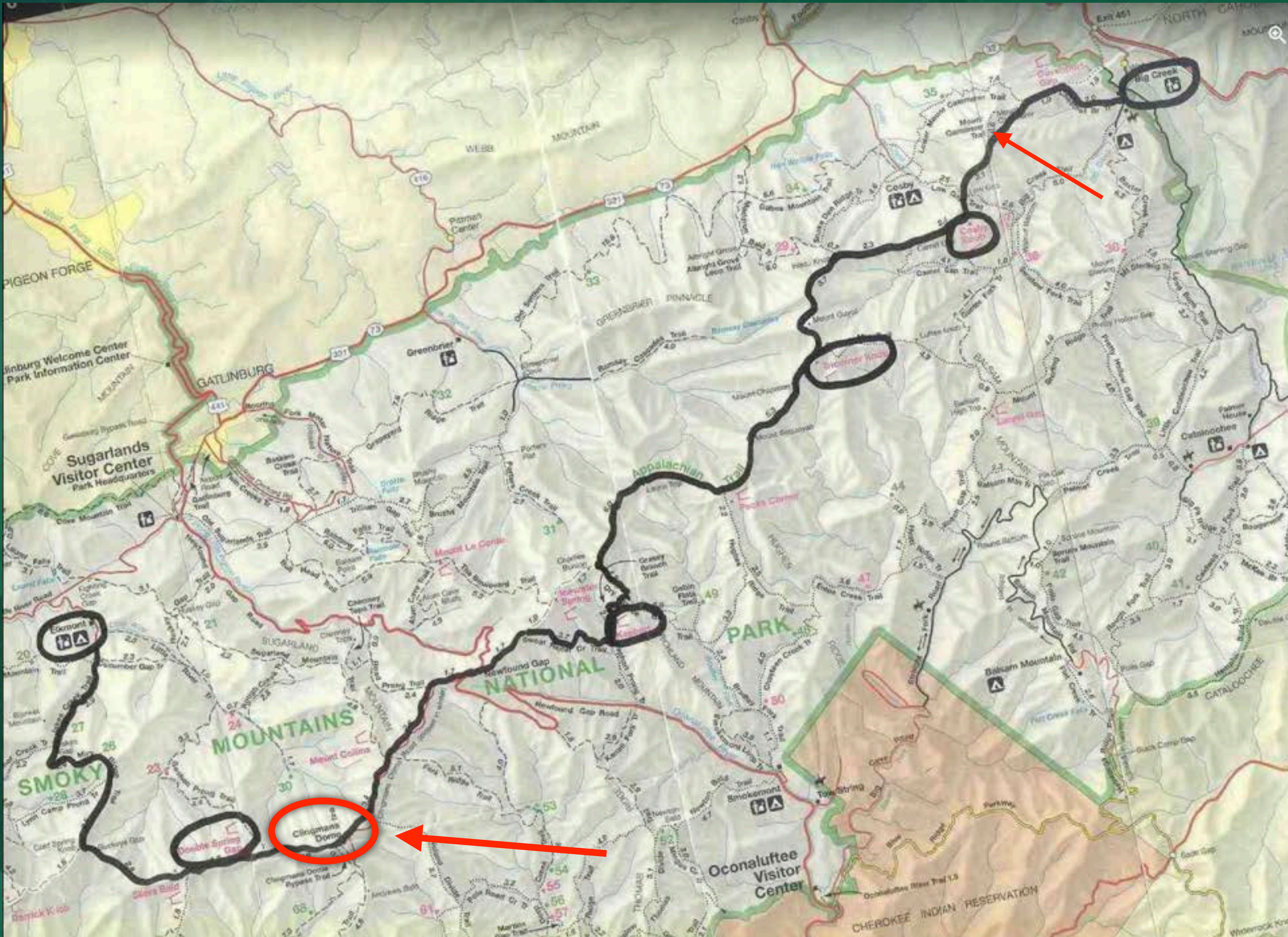
1) Earth's atmosphere is not the same in every location on the planet.

(*3rd dimension: altitude*)

LOCATION	ELEVATION (ft.)	ATMOSPHERIC PRESSURE $P_B=760(e^{-a/7924})$ (mmHg.)	OXYGEN PRESSURE (= 21% atmospheric pressure) (mmHg.)
Gulf Shores	0	760	160
Birmingham	650	740	155
Cades Cove	1800	710	150
Spence Field	4900	635	133
Newfound Gap	5050	630	132
Clingman's Dome	6643	595	125
Thunderhead	5500	620	130
Jackson Hole	6447	600	126
Yellowstone Lake	7730	570	120
Grant Village	7810	570	120
Old Faithful	7400	580	122
Jackson Lake	6772	590	124
Colter Bay Village	6840	590	124
Jenny Lake	6783	590	124
Inspiration Point	7200	585	123
Fork of Cascade Canyon	7800	560	118
Lake Solitude	9035	540	113
Paintbrush Divide	10700	520	109
Holly Lake	9410	530	111
Hurricane Pass	10400	520	109
Alaska Basin	8900	540	113
Death Canyon Trailhead	6800	590	124
Death Canyon Shelf	9500	530	111
Fox Creek Pass	9560	530	111
Lupine Meadows trailhead	6700	590	124
Surprise Lake	9700	525	110
Mt. Everest	29035	225	47



PIGEON FORGE
WEBB
MOUNTAIN
Pittman Center
Greenbrier
GATLINBURG
Sugarlands
Visitor Center
Park Headquarters
Cosby
Big Creek
Exit 451
Appalachian Trail
Cataloochee
CATALOOCHEE
Balsam Mountain
Elkmont
SUGARLAND
Newfound Gap
Newfound Gap Road
NATIONAL
PARK
SMOKY
MOUNTAINS
Mount Collins
Mount Le Conte
Clingmans Dome
Double Spring Gap
Smokemont
Oconaluftee
Visitor
Center
CHEROKEE INDIAN RESERVATION

Mt. Cammerer
4,928 ft.

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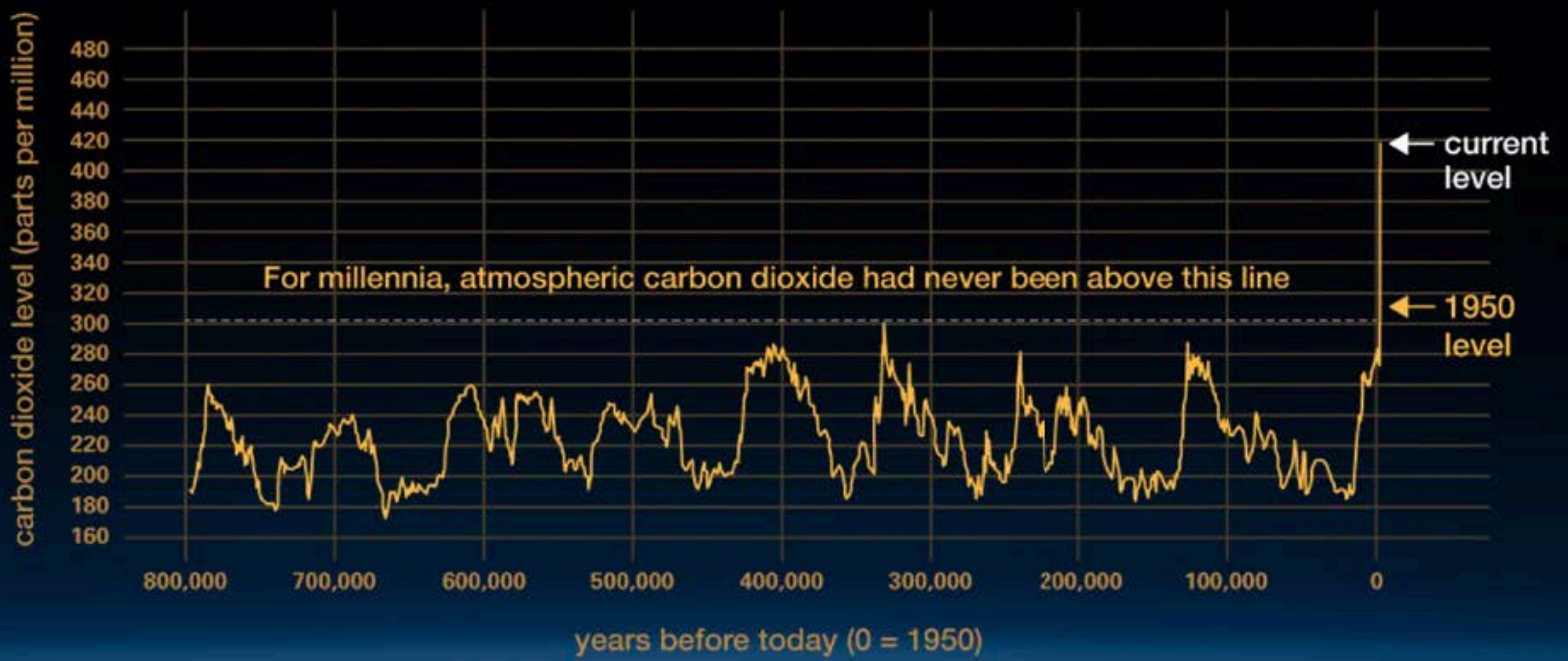
Current atmosphere:
78% N_2
21% O_2
0.9% Ar
0.04% CO_2

HIGH ALTITUDE PHYSIOLOGY

The adaptability of human physiological processes to significant variations in environmental conditions is remarkable. The ability of the respiratory system to modify its function in response to altitude is an example. As seen in the last issue of this guide, there is a decreasing partial pressure of oxygen (O_2) as one ascends. Carbon dioxide (CO_2), the other major gas of importance in cellular respiration, also diminishes in pressure, but its content is negligible (0.04%) in the present earth atmosphere.

Interestingly, CO_2, not O_2, is the gas that normally regulates minute-to-minute ventilation (breathing). As the level of CO_2 increases in the blood, the acidity of the blood increases slightly (pH decreases); specialized neurons in the brainstem sense this and cause an increased ventilatory drive (heavier breathing). This is the usual control system of breathing. In the normal circumstance, if the lungs/ventilatory system is maintaining adequately low CO_2 levels, the O_2 levels will be just fine.

However:



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HIGH ALTITUDE PHYSIOLOGY

Acute Mountain Sickness (AMS)

As discussed in the second issue of this guide, it is the adaptive transfer of ventilatory control from the predominant central (brainstem) CO_2/pH receptors to the peripheral (aortic/carotid body) O_2 chemoreceptors that characterizes acclimatization to increased altitude. This adjustment takes a variable amount of time and individuals vary in their ability to acclimatize. Interestingly, an individual's level of physical conditioning / fitness does not predict readiness of acclimatization or tendency to develop AMS.

As it turns out, the altitudes that we will be experiencing in Yellowstone and the Grand Tetons are just at the borderline where AMS might be considered likely. It would be different if we were planning ascent of Grand Teton peak (13770 ft.), at which altitude, AMS symptoms of some degree might be expected in >25% of people.

So, what is AMS, what causes it, what are the symptoms, how can its likelihood be diminished? Hypoxemia (relatively low O_2 levels in the blood) is the abnormality that results in the changes that cause AMS symptoms. As mentioned, there is a period of acclimatization to altitude during which hypoxemia (low O_2 in the blood) is not sufficient to drive the ventilatory rate upward to correct the problem, since the CO_2/pH regulation dominates control of ventilation.


Grand Teton summit: 13,770 feet
Atmospheric pressure: 448 mmHg
PIO_2: 94 mmHg


… near Mt. Whitney summit

oldest and youngest sons on Mt. Whitney summit

August 2018 Mt. Whitney trek

Atmospheric pressure: 440 mmHg

PIO_2: 93 mmHg

Apiopolis apiary

in Aldridge Gardens

See: imagessays.com/#/apiopolis

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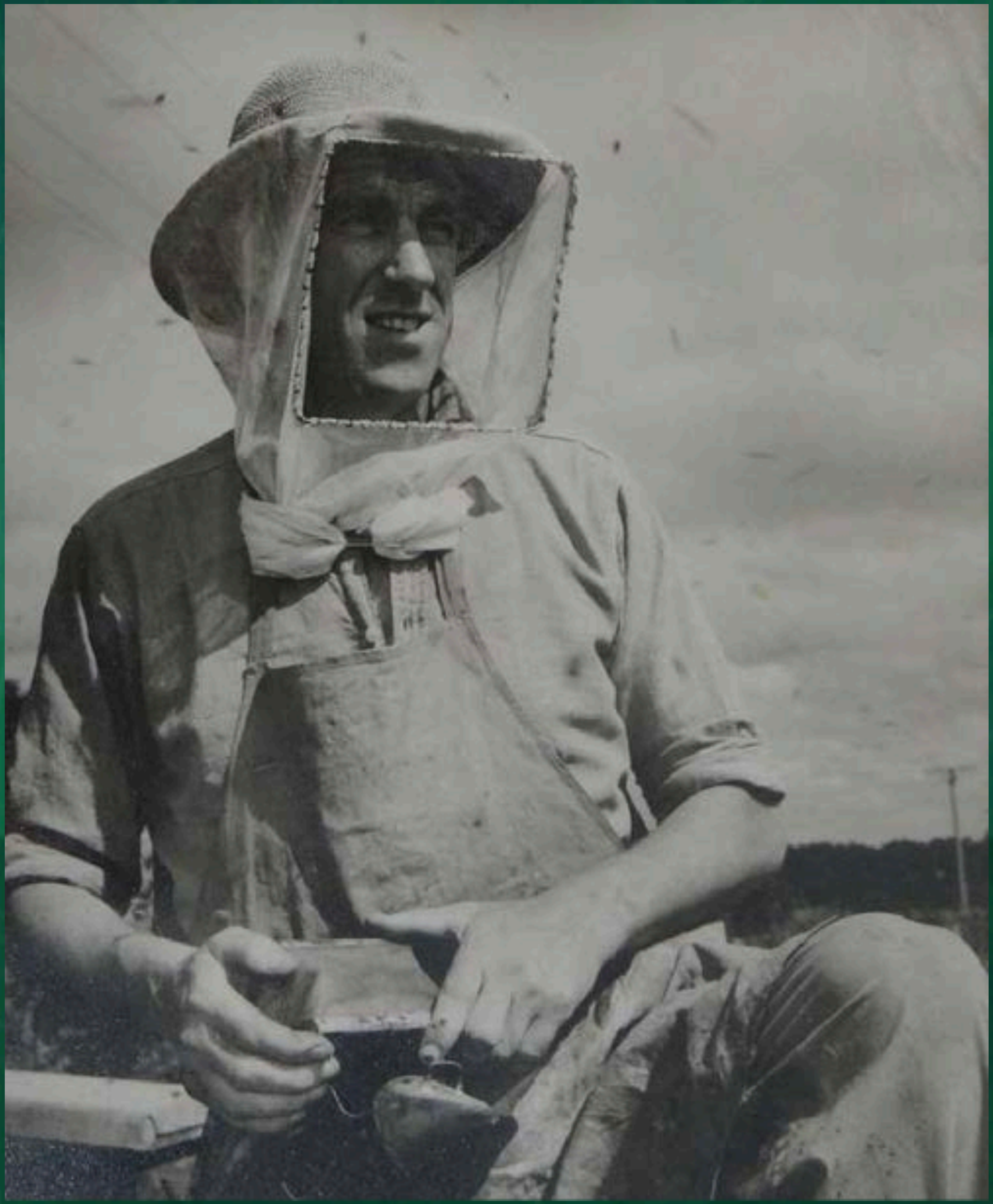
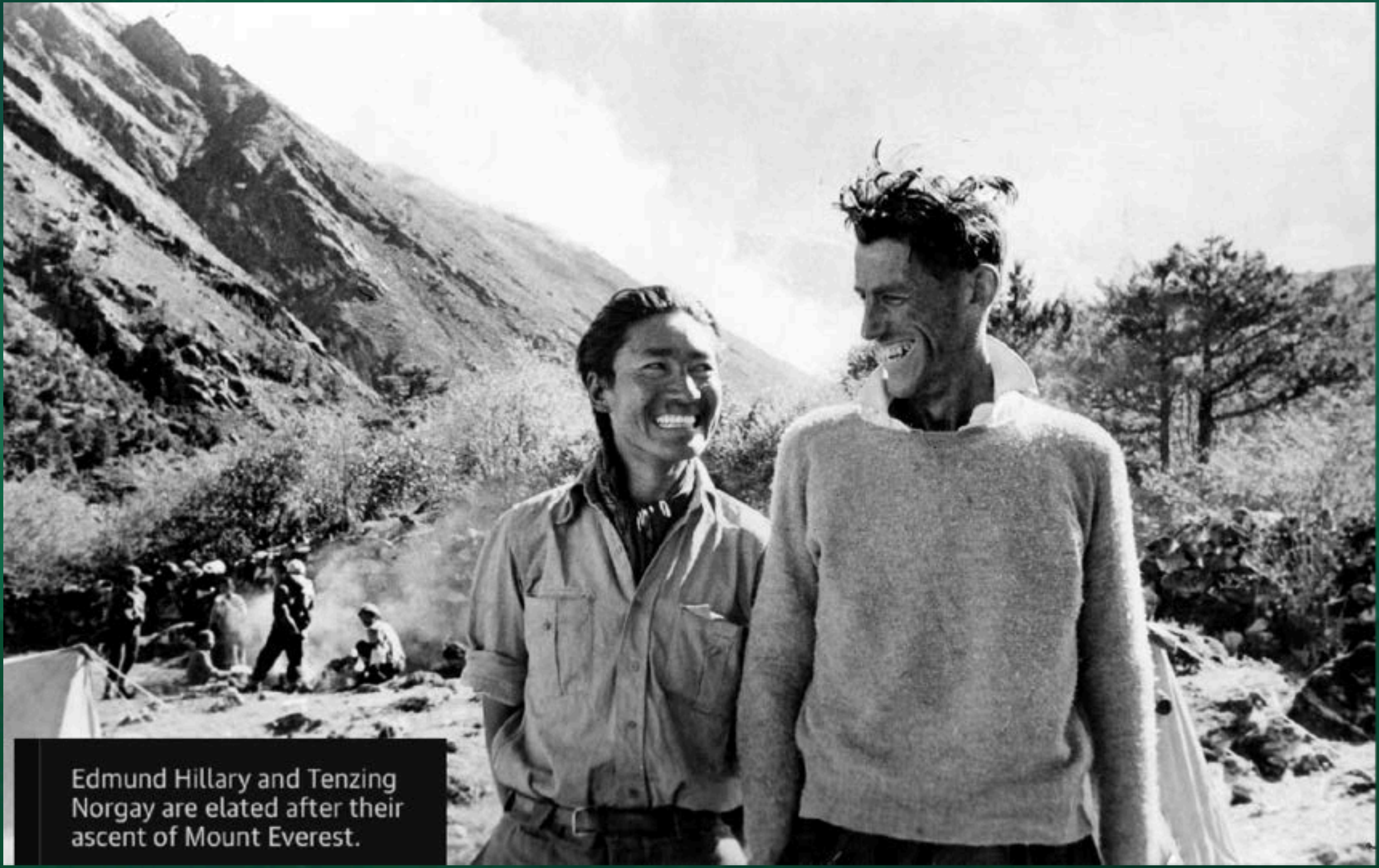
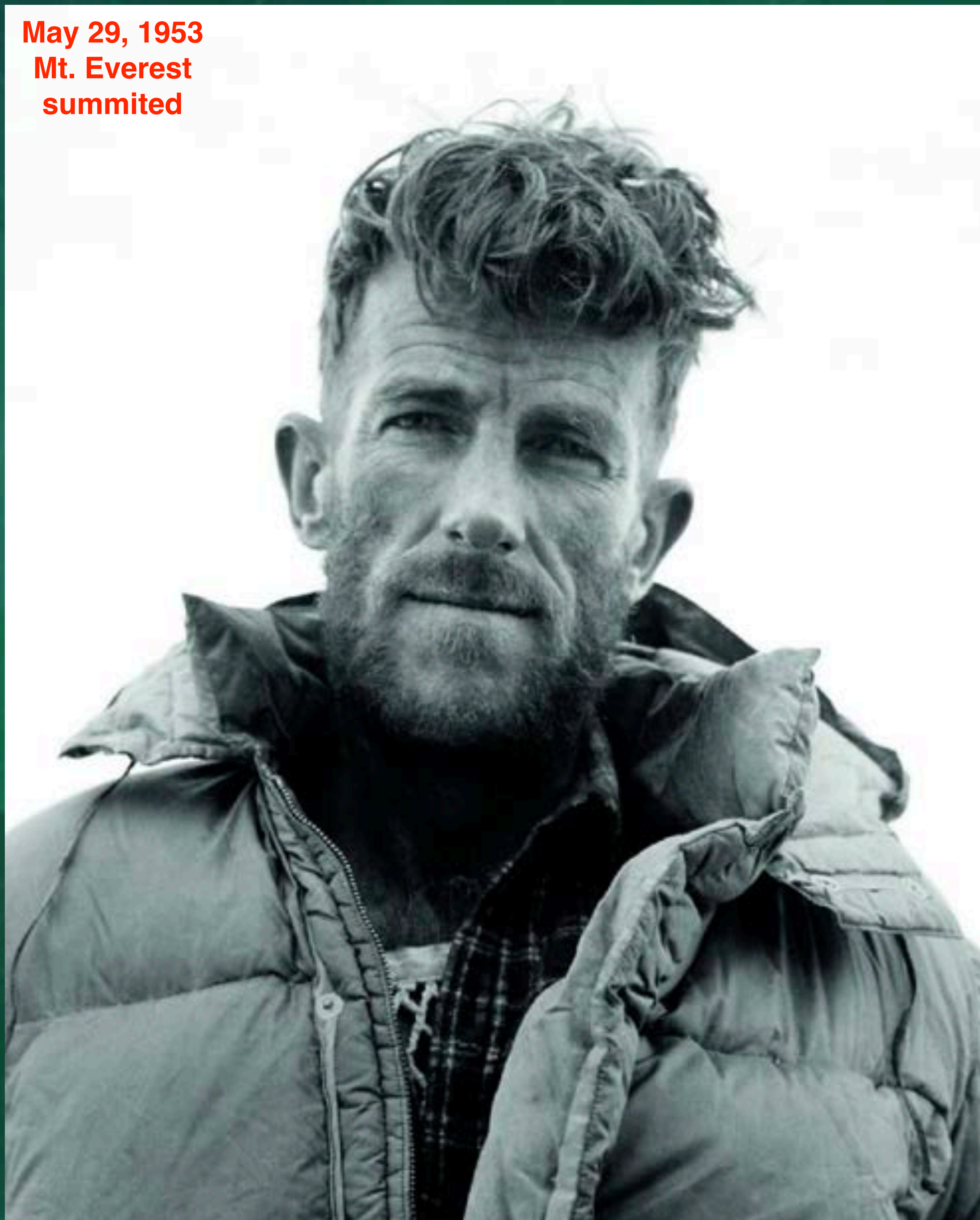


New Zealand beekeeper
Edmund Hillary

On May 29, 1953, mountaineers Edmund Hillary and Tenzing Norgay set foot atop Mount Everest, the world's highest mountain. They were the first ever to reach its 29,029-foot peak.



Edmund Hillary and Tenzing Norgay are elated after their ascent of Mount Everest.


May 29, 1953
Mt. Everest
summited


June 2, 1953
Queen Elizabeth II
crowned
On June 2, 1953, Princess Elizabeth was crowned as Queen Elizabeth II.


June 6, 1953
Sir Edmund Hillary
knighted
On June 6, 1953, Edmund Hillary was appointed Knight Commander
of the Order of the British Empire
Sir John Hunt (L), leader of the British Everest expedition, and Sir Edmund Hillary (R) arrive at Lancaster House for reception being given in their honor. Earlier they had been received by Queen Elizabeth who knighted the two men.

... also in 1953:

- 1953. John Gibbon
  - the first successful cardiac surgery(ASD repair) using a pump-oxygenator

Jefferson Medical College
Philadelphia

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Knowledge that will change your world

… two years later:

- 1955. John Kirklin
  - the second successful cardiac surgery(VSD repair) using a pump-oxygenator('Mayo-Gibbon bypass machine')

For a brief period of time (1955–1956), there were only 2 hospitals in the world where open heart surgery was being done on a daily basis: Lillehei at the University of Minnesota and, 60 miles away, John Kirklin at the Mayo Clinic. Surgeons came in droves from all over the world to see these 2 men at work.

In 1966, Dr Kirklin became surgeon-in-chief and chairman of the Department of Surgery at UAB.

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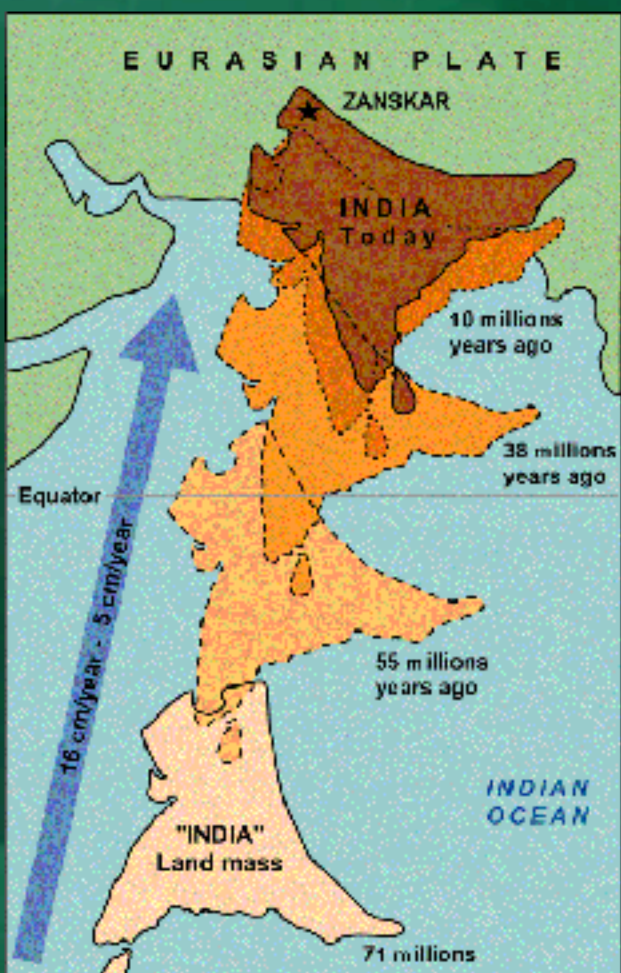
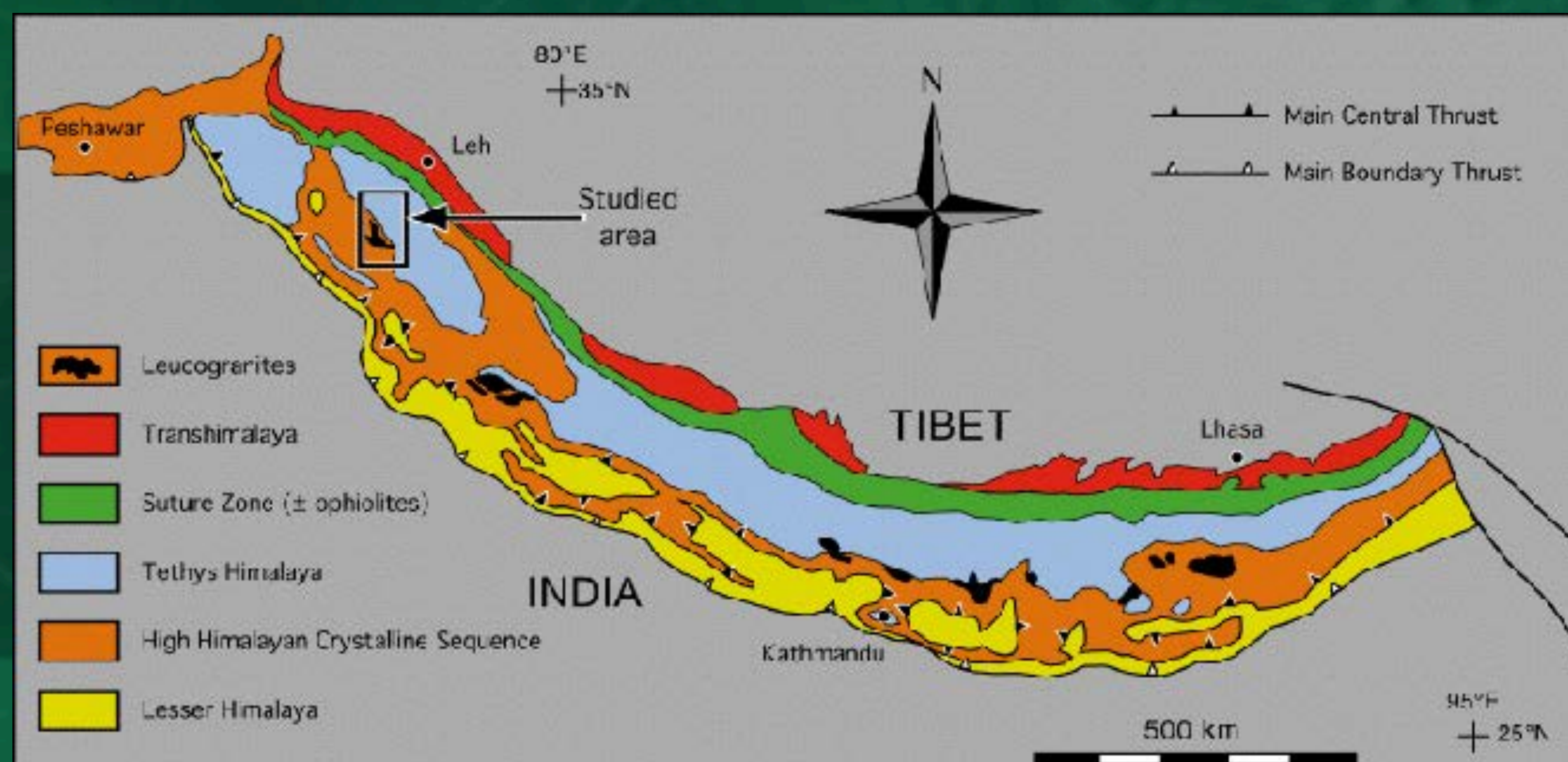
Knowledge that will change your world

Earth in the Cretaceous

Mount Everest



tectonic plate movement



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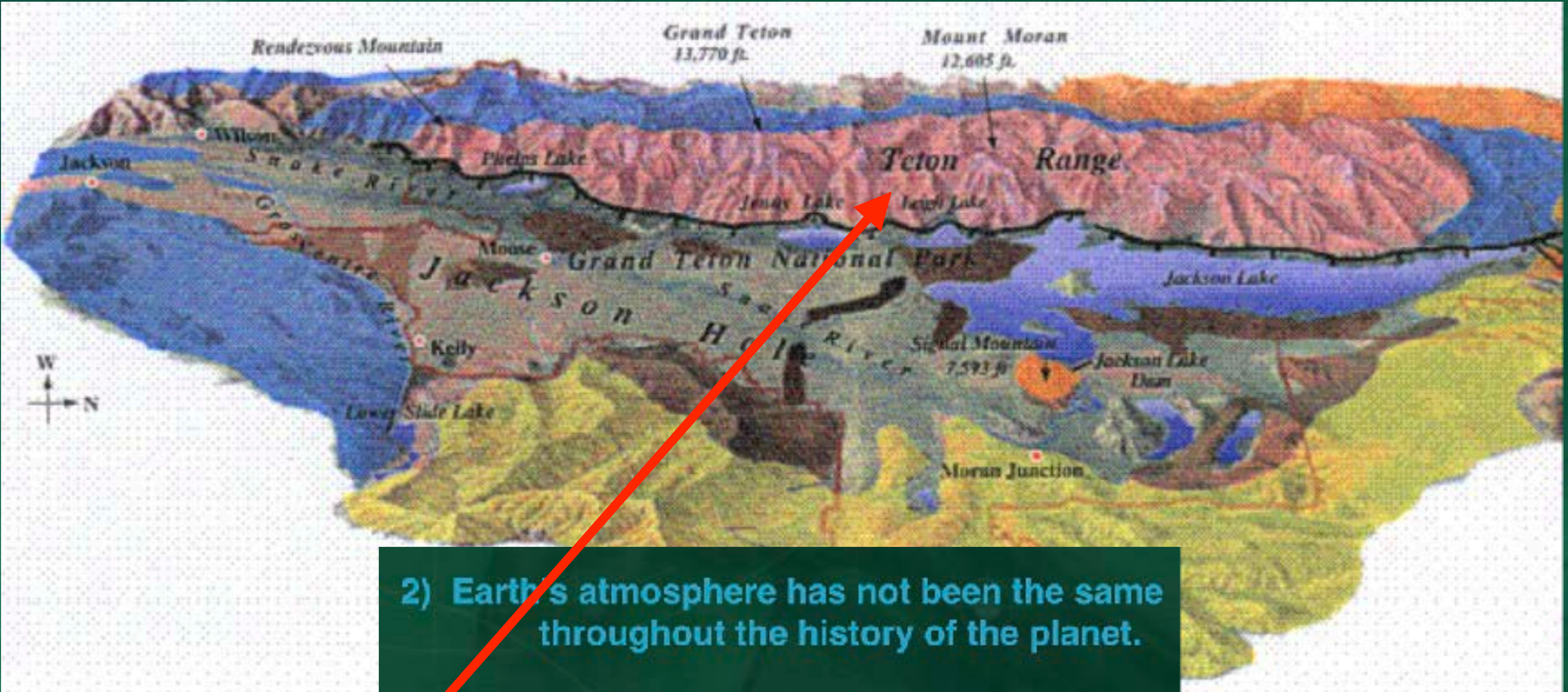

2) Earth's atmosphere has not been the same throughout the history of the planet.

(*4th dimension: time*)

Legend

- 2.8 and 1.5 billion year old crystalline basement: granitic and metamorphic rocks.
- 540 to 245 million year old rocks primarily deposited in a deep ocean: limestone, sandstone, shale and dolomite.
- 245 to 66 million year old rocks deposited mainly in a shallow ocean: siltstone, limestone, sandstone, gypsum, conglomerates, coal beds and shale.
- 60 million to 3 million year old volcanic conglomerates, tuff, clay stone, sandstone deposited in shallow lakes accompanied by local volcanism.
- 2 million year old rhyolite and welded tuff deposited during Yellowstone's first giant, caldera-forming volcanic eruption.
- 150,000 to 14,000 year old glacial outwash and till deposited by glaciers.
- 1.6 million year old to present, landslide and stream deposits, gravel, sand and alluvium.

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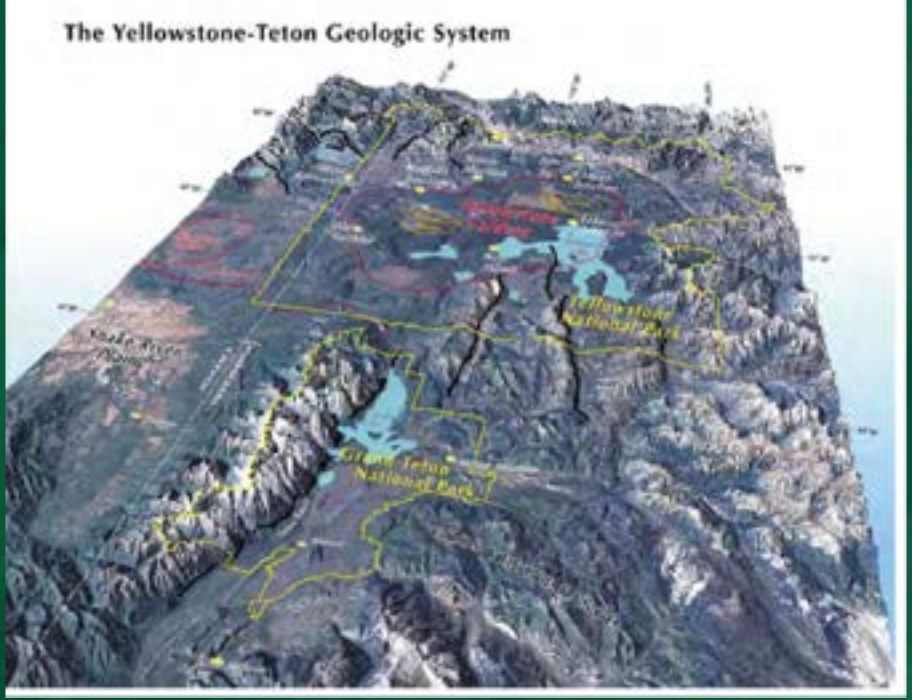
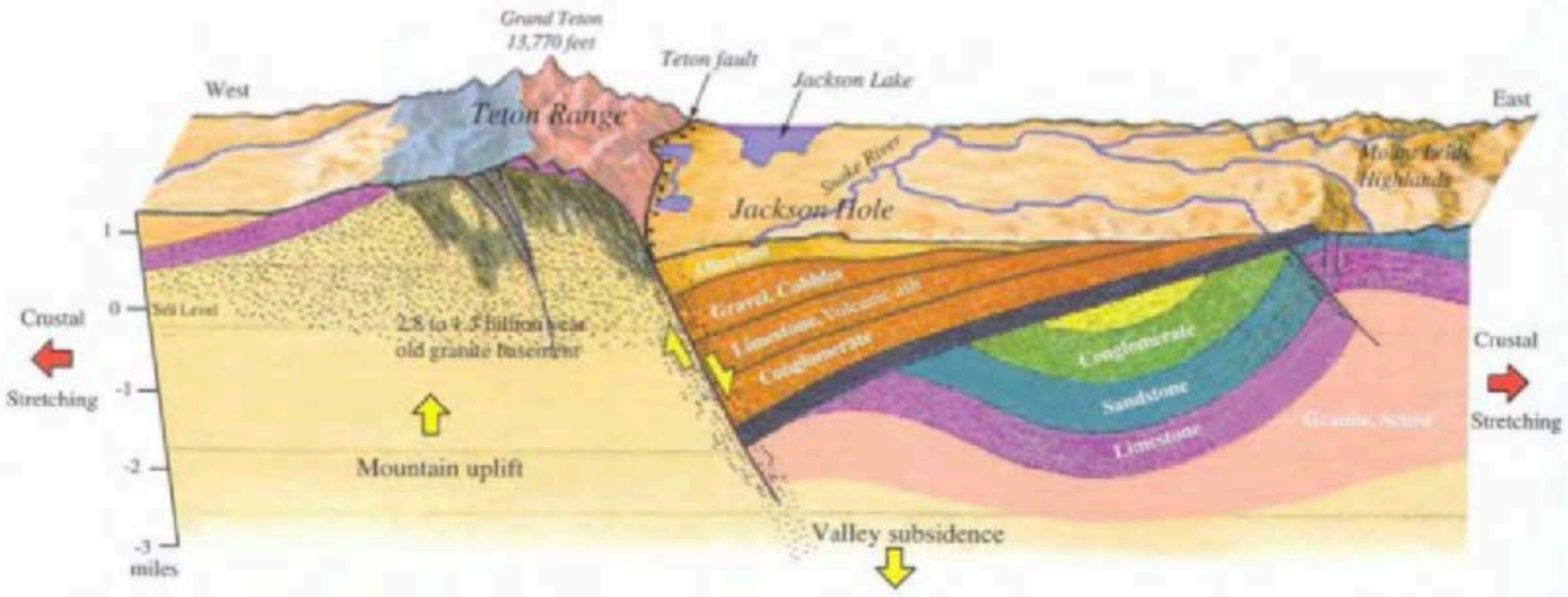
2) Earth's atmosphere has not been the same throughout the history of the planet.

(*4th dimension: time*)





5.3 ~ *Cross section showing the fault-caused westward tilt of rocks on the west side of the Teton Range and beneath Jackson Hole. Total movement on the Teton fault and from earlier mountain-building is about 6 miles, which is the elevation difference between rock layers high in the mountains and their projected location beneath Jackson Hole.*

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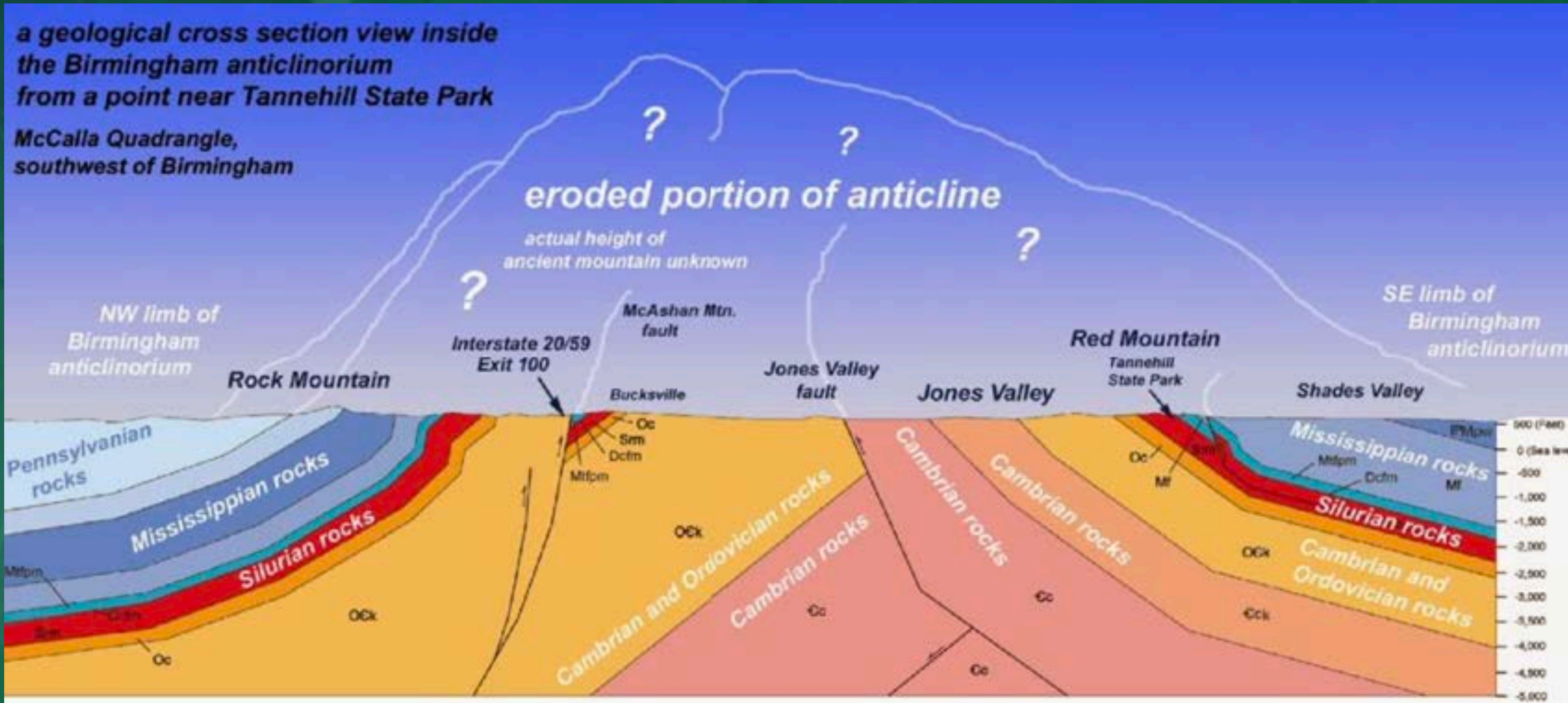
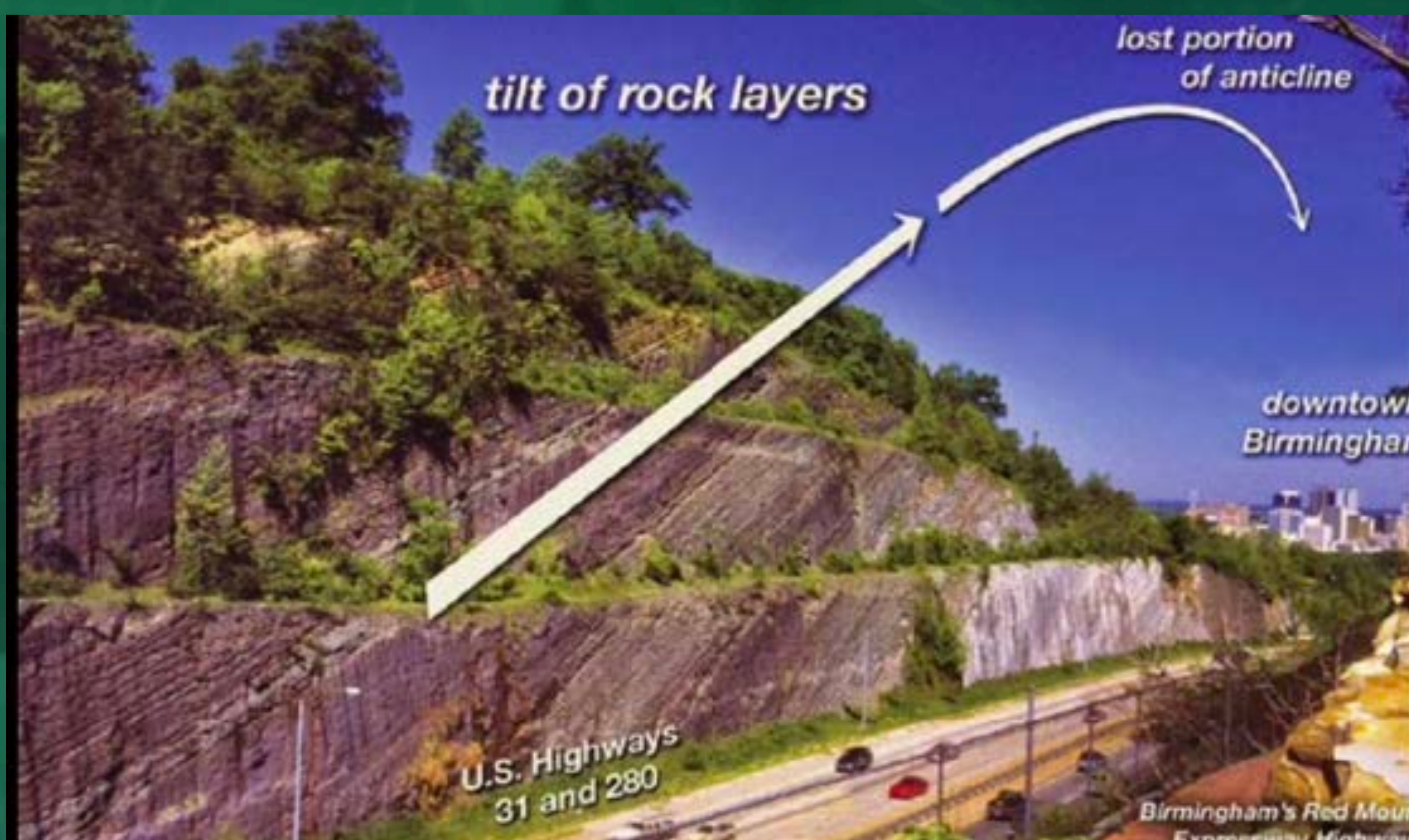
Red Mountain Cut: opened 1970





Digging and grading took 7 years, from 1962 to 1969, and the cut was opened to traffic in 1970. The removal of 2 million cubic yards of the ridge of Red Mountain exposed over 190 million years of geologic strata dating to over 500 million years ago.

The Ordovician, Silurian, Devonian and Mississippian geologic periods are visible in the cut. Special features include caves, volcanic ash layers, the Red Mountain fault line, prehistoric reefs and beaches, fossils, and fossil tracks.

Significantly, the cut reveals the cross-section of the red ore seam that spurred Birmingham's development and a layer containing fossils of a unique Silurian trilobite species.

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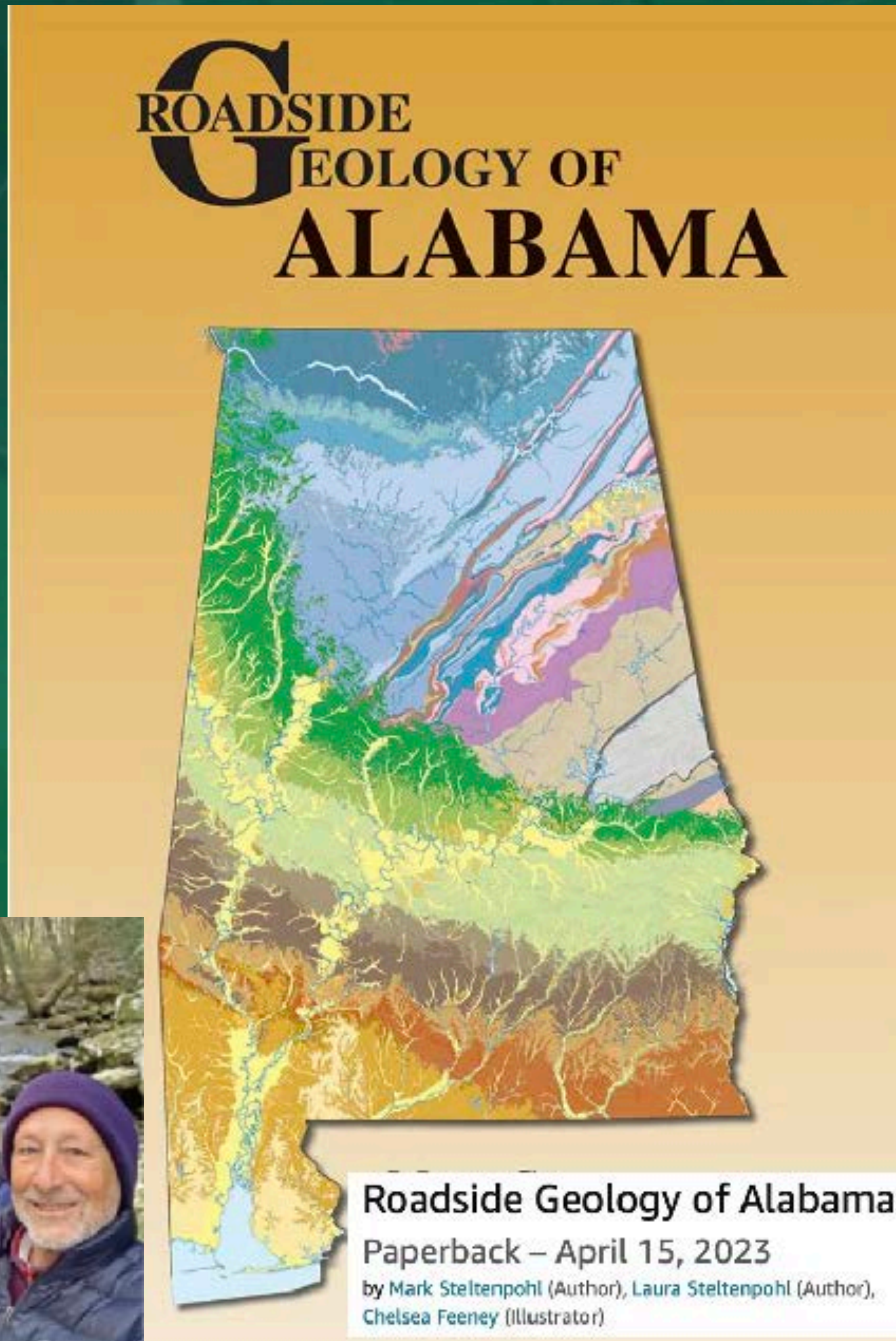

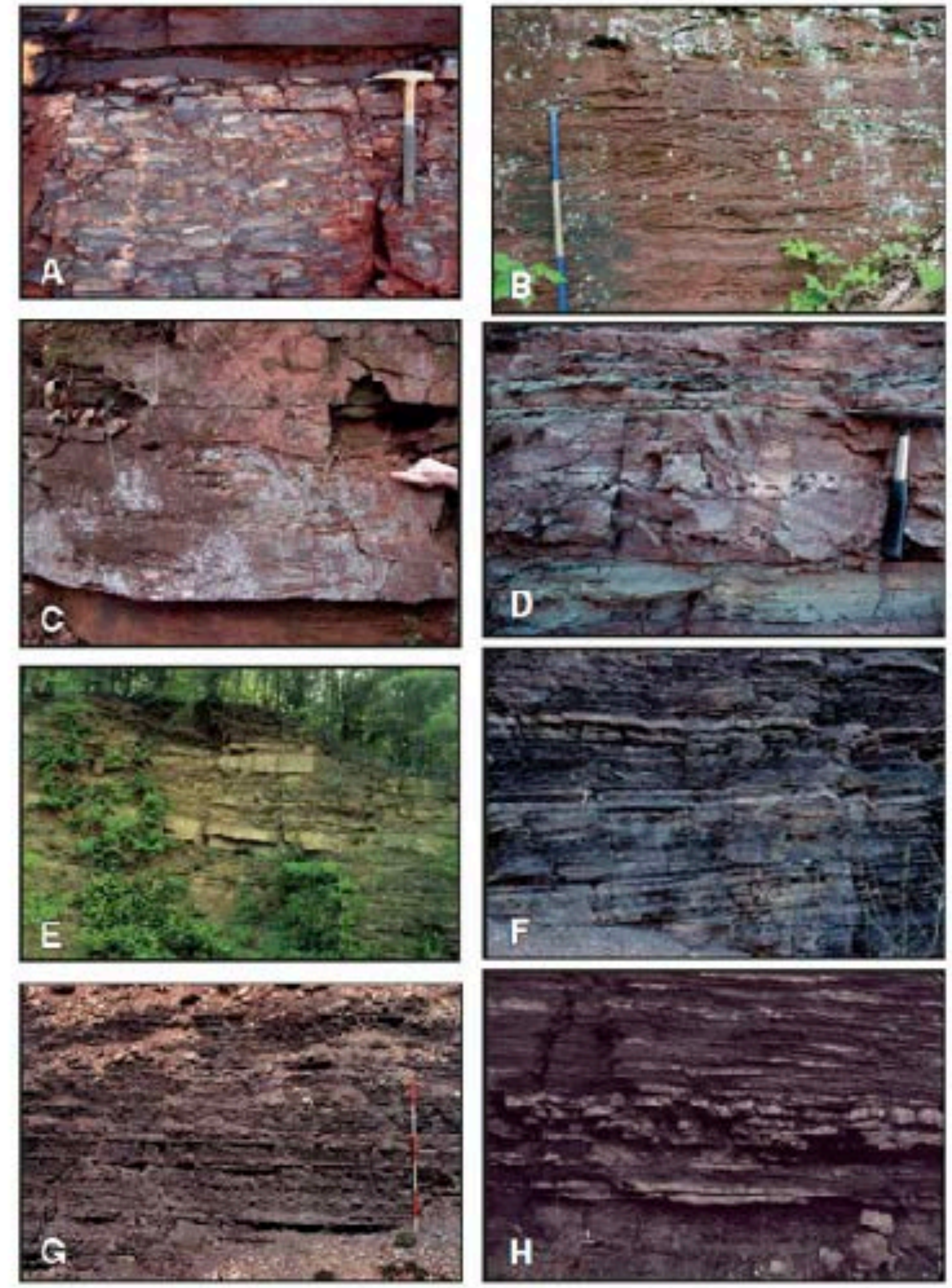

Figure 6. Major lithofacies in Red Mountain Formation. Jacob staff scaled in feet, hammer ~1 foot. (A) Facies 1 Conglomeratic ravinement lag from the Kidney bed between the Big and Irondale seams at the type section. Intraclasts include lithified and unlithified ironstone and limestone. (B) Facies 1. Cross-bedded ironstone from tidal inlet facies, Merrow Gap beds at Ruffner Mines, Alabama. (C) Facies 1. Bimodal (herringbone) cross-beds from Merrow Gap tidal channel, Ruffner Mines, AL. (D) Facies 1. Cross-bedded tidal-delta sandstone interbedded with estuarine shale, Walker Gap beds, type section. (E) Facies 3. Hummocky cross-bedded sandstone facies, Taylor Ridge Member, Estelle, Georgia. (F) Facies 5. Thin, fine-grained graded sandstones (storm beds) interbedded with shale, Taylor Ridge Member, Ringgold, GA. (G) Facies 5. Shale with thin siltstone storm beds, base of Taylor Ridge Member, Ringgold, GA. (H) Facies 6. Interbedded limestone–shale facies; base of Birmingham Member, Duck Springs, AL.

Stratigraphy and depositional environments in the Silurian Red Mountain Formation of the southern Appalachian basin

The Geological Society of America - Field Guide 39 - 2015

Timothy M. Chowns - Department of Geosciences, University of West Georgia*
Andrew K. Rindsberg - Department of Biological & Environmental Sciences, University of West Alabama*

Mark Steltenpohl is an emeritus professor at Auburn University with more than 40 years of experience as a field geologist. Laura Steltenpohl taught science for 20 years at Auburn High School, mostly Chemistry, Physics, and Earth Science.

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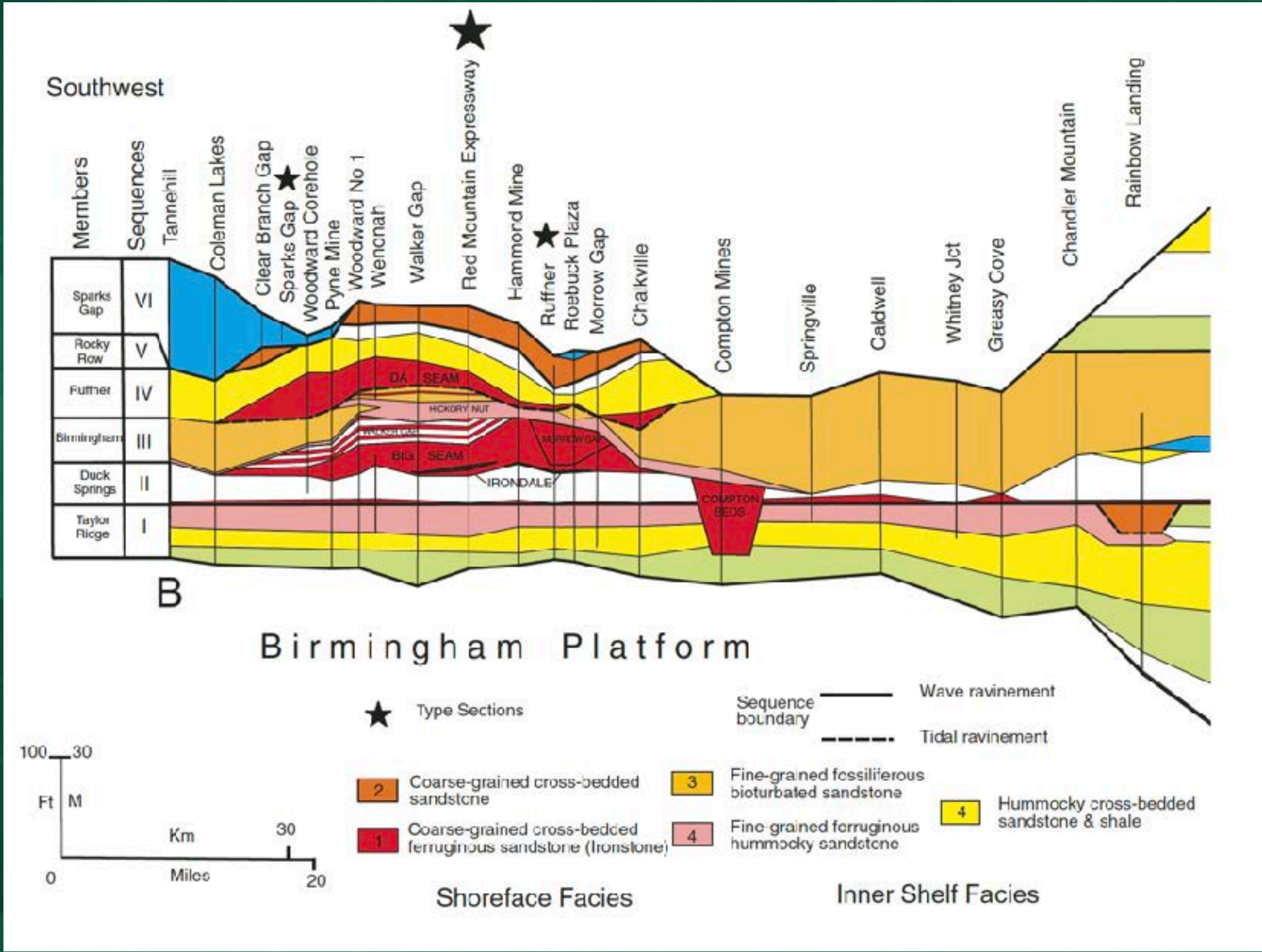
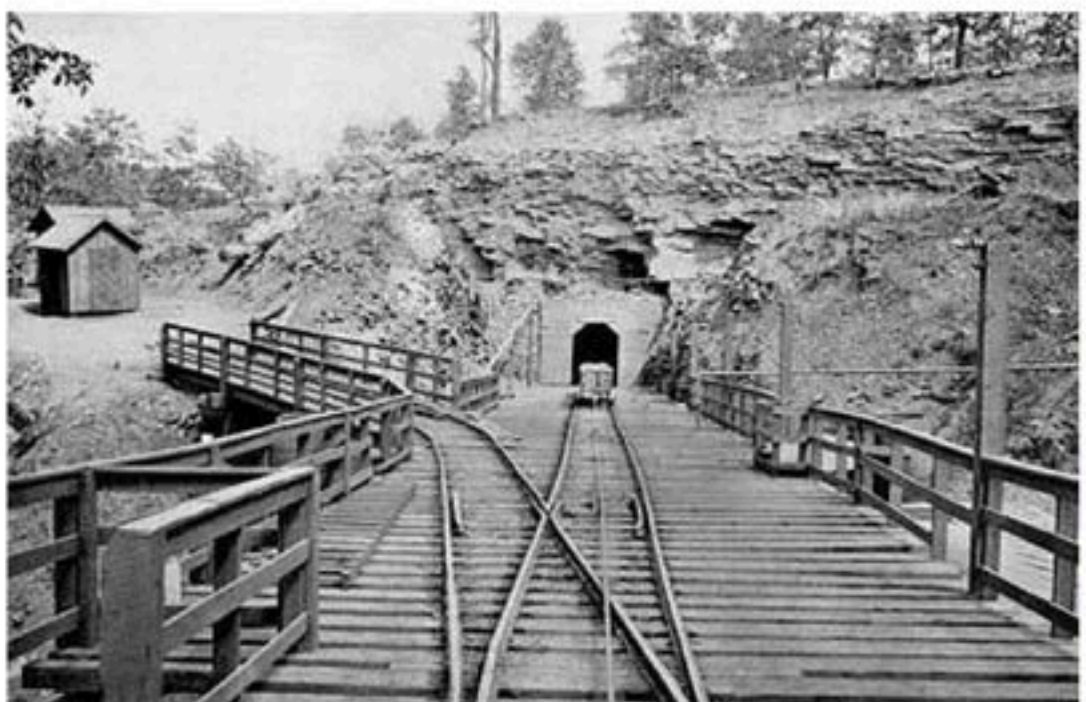
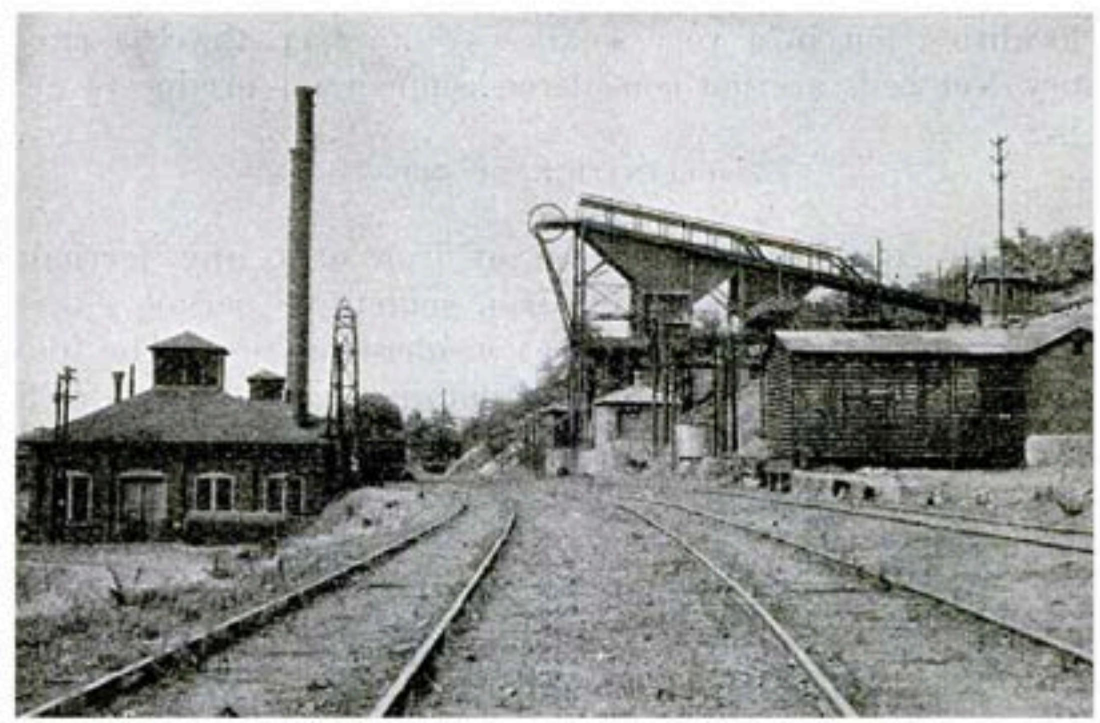

Southwest
Members
Sequences
Tannehill
Coleman Lakes
Clear Branch Gap
Sparks Gap
Woodward Corehole
Pyne Mine
Woodward No 1
Wenonah
Walker Gap
Red Mountain Expressway
Hammond Mine
Ruffner
Roebuck Plaza
Morrow Gap
Chalkville
Compton Mines
Springville
Caldwell
Whitney Jct
Greasy Cove
Chandler Mountain
Rainbow Landing
Sparks Gap
VI
Rocky Row
V
Ruffner
IV
Birmingham
III
Duck Springs
II
Taylor Ridge
I
IDA SEAM
HICKORY NUT
BIG SEAM
IRONDALE
COMPTON BEDS
B
Birmingham Platform
Type Sections
Sequence boundary
Wave ravinement
Tidal ravinement
100 30
Ft M
Km 30
0 Miles 20
2 Coarse-grained cross-bedded sandstone
1 Coarse-grained cross-bedded ferruginous sandstone (Ironstone)
3 Fine-grained fossiliferous bioturbated sandstone
4 Fine-grained ferruginous hummocky sandstone
4 Hummocky cross-bedded sandstone & shale
Shoreface Facies
Inner Shelf Facies

There are both Red Iron Ore (Hematite) and Brown Iron Ore (Limonite) deposits in the vicinity of Birmingham. These deposits are the southeastern continuation of the Silurian Clinton Iron Formation which extends from New York State along the Appalachian Mountains. Red Mountain on the east side of the city was the location for most of the iron mines. Many antebellum charcoal furnaces utilized the Brown Limonite Ore; however, after the Civil War, the mainstay of the iron and steel industry was the Red Mountain Hematite Ore. The hematite ore beds were in the Red Mountain Formation with a dip of about 16°. The greatest production came from the “Big Seam.“ This seam was 15-22 feet thick and divided into parts by a small bed of slate. Smaller amounts of production came from the thinner Ida and Irondale Seams located above and below the Big Seam respectively.



Entrance to a Red Mountain Underground Iron Mine, ca1908.. (Library of Congress)



Ore tipple and railroad loading facilities at a Red Mountain Iron Ore Mine, ca1923. (USBM)

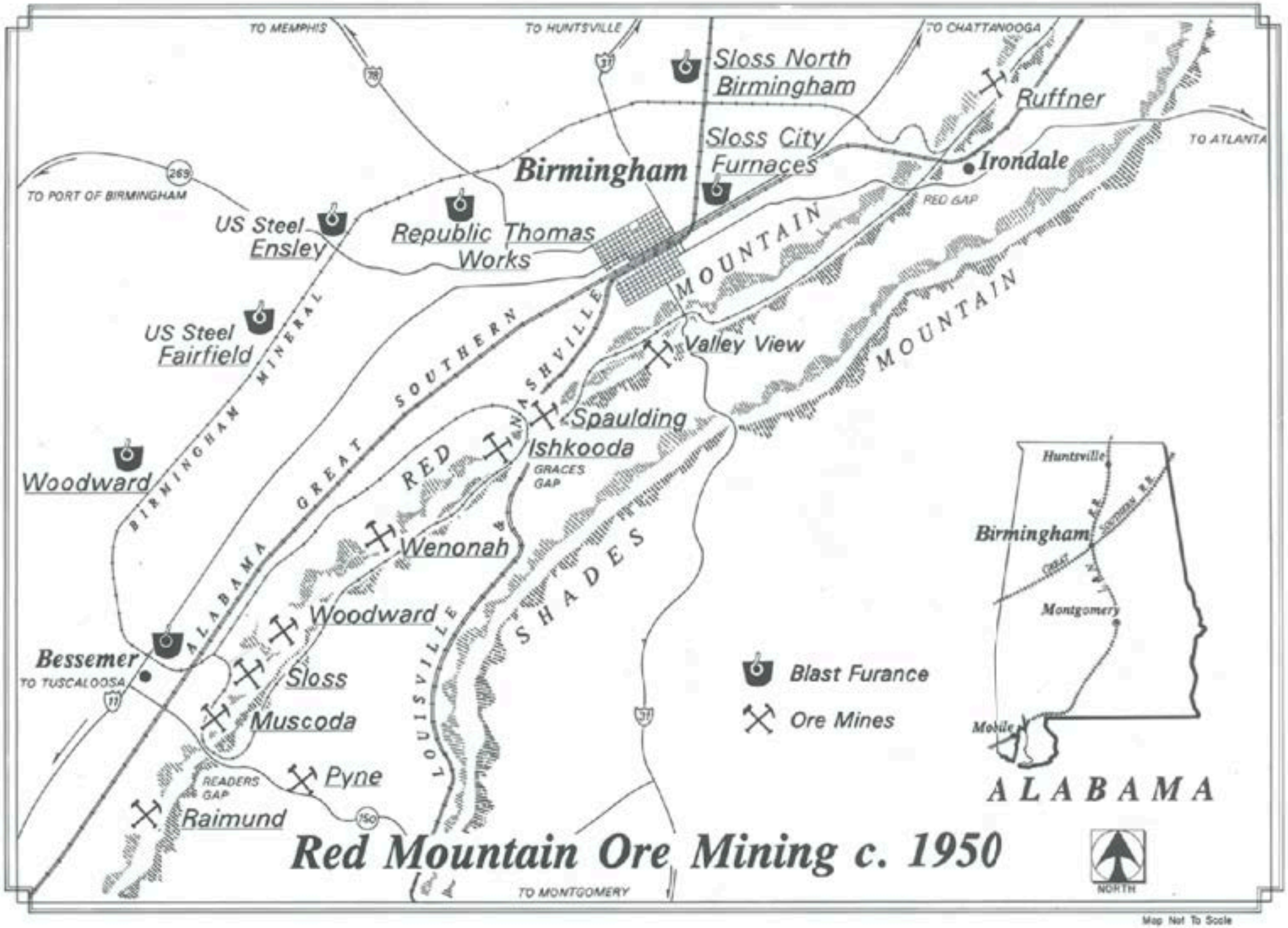


Figure 16. Location of major mines along Red Mountain. (From Morris and White, 1997.)


1970

See: Red Mountain Cut Project pics

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DOWNTOWN
BIRMINGHAM
RED MOUNTAIN CUT
TRAIL
MINE ENTRANCE
GATEWAY
20TH AVE. S.
ON-STREET TRAIL TO
21ST AVE S.
&
ON-STREET PARALLEL
PARKING
21ST STREET SOUTH
BECOMES ONE-WAY

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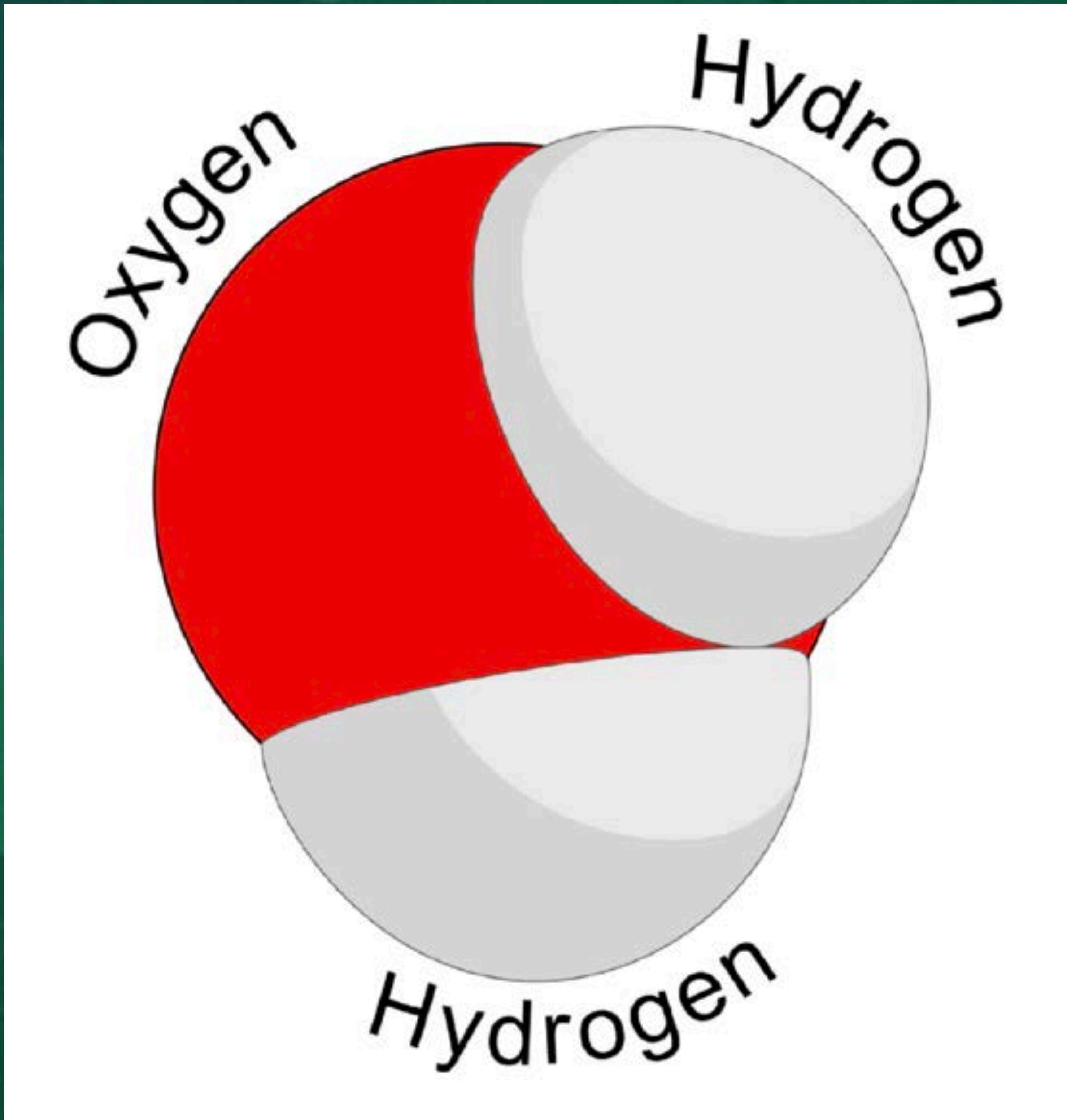
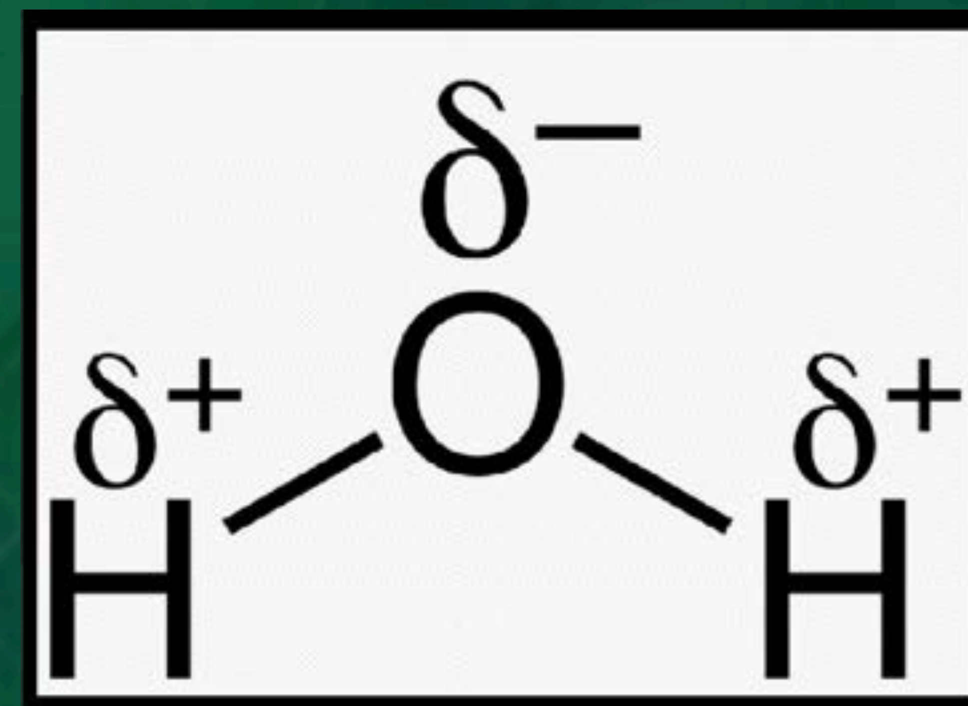
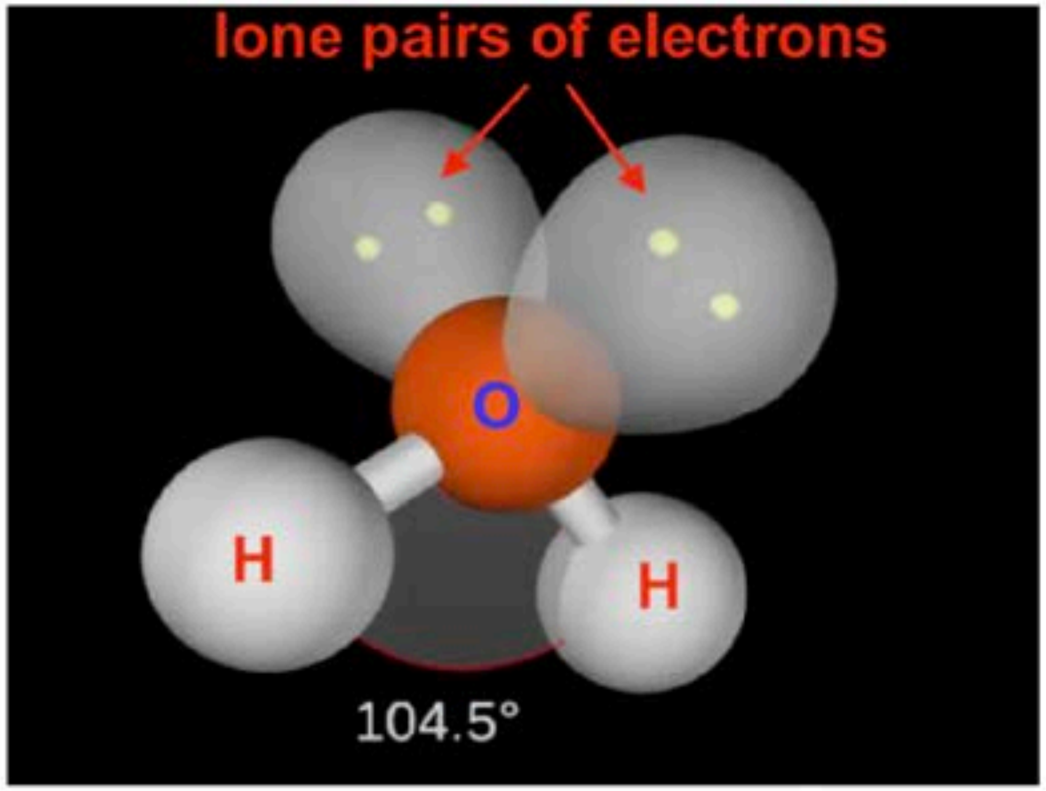
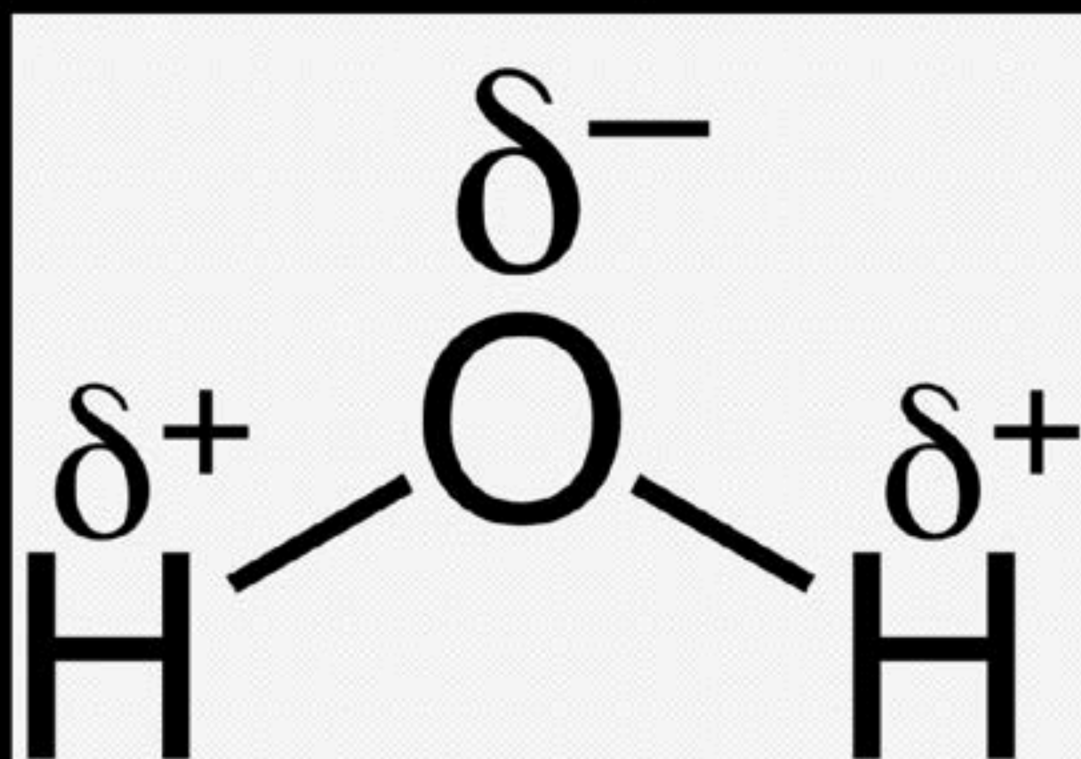


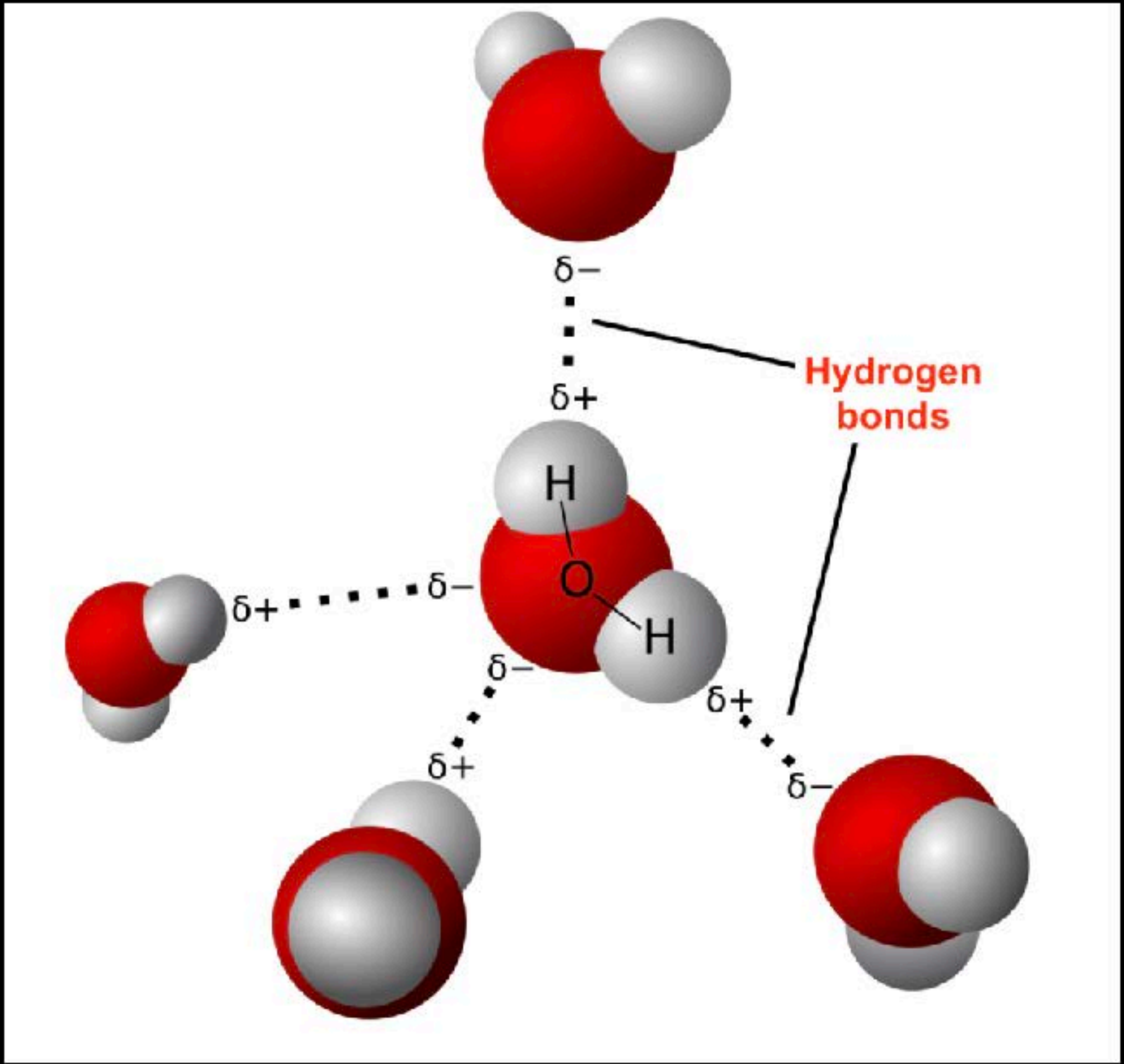


The angular structure of the H_2O molecule results in its *electrical polarity*, which is necessary for the function of membranes, which are the *essential boundaries of living cells*.



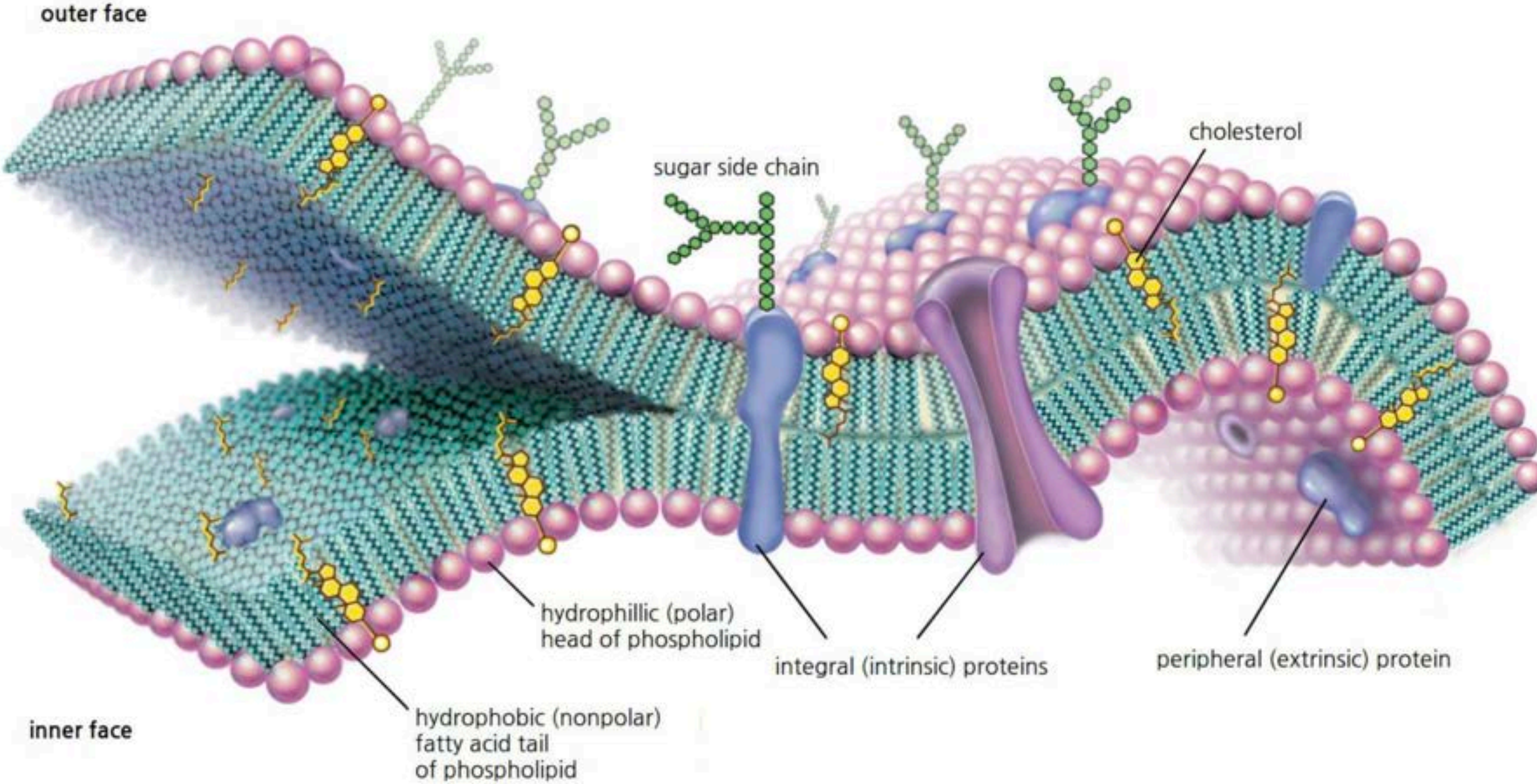
There are six electrons in the outer orbital of an oxygen atom. In a water molecule, two of these electrons bond with the lone electron of each hydrogen atom to form two "bond pairs". The remaining four oxygen electrons pair up to form two "lone pairs". (It is energetically favorable for electrons with opposite spins to form pairs.)





The weak hydrogen bonds formed between water molecules are responsible for many of the unique properties of liquid water.

The *bipolar lipid membrane* always forms the boundary of every cell, separating the aqueous internal living system from the aqueous external nonliving environment.

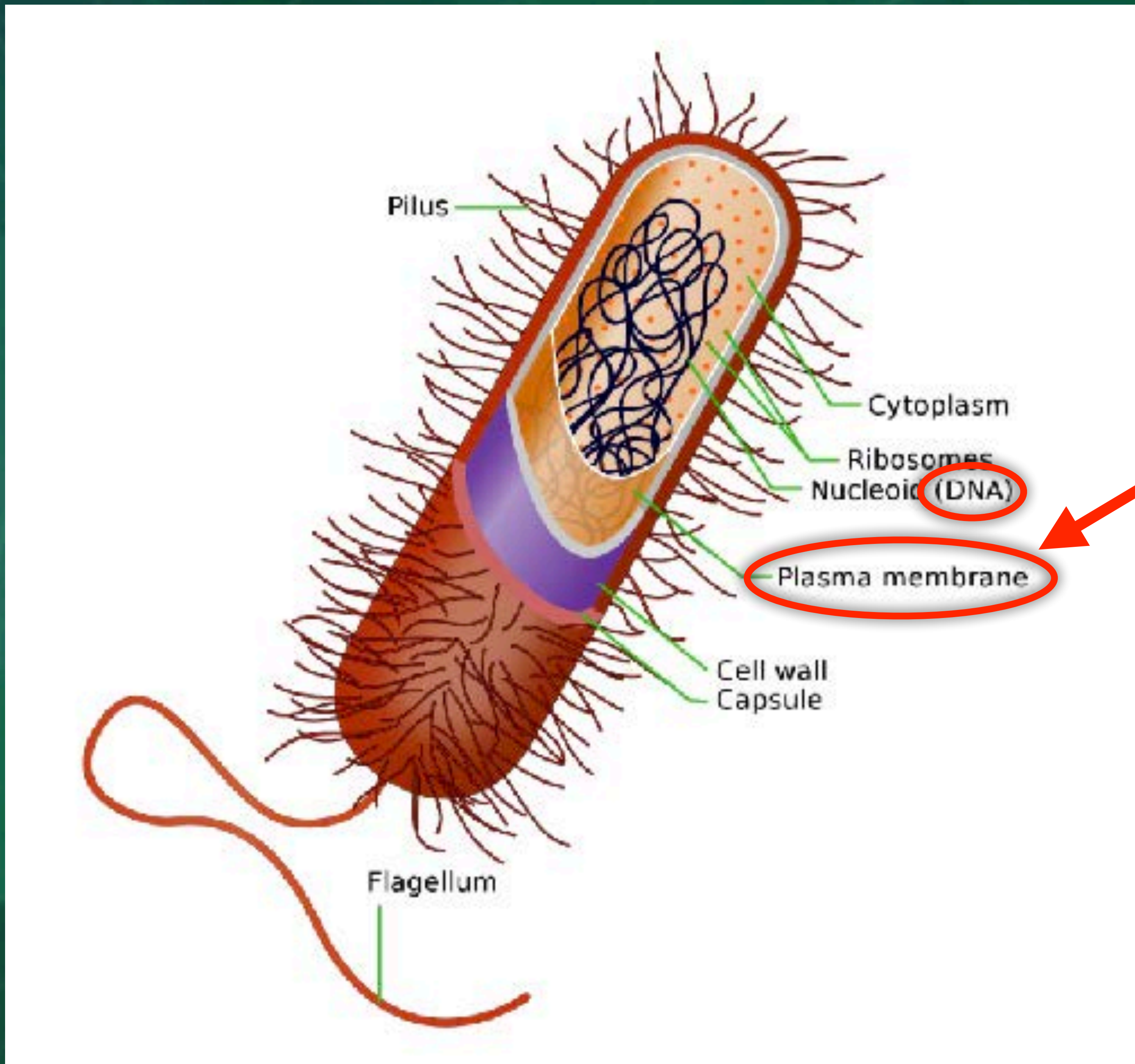


Rudolph Virchow is best remembered today for his succinct proclamation (1858) of one of biology's universal laws:

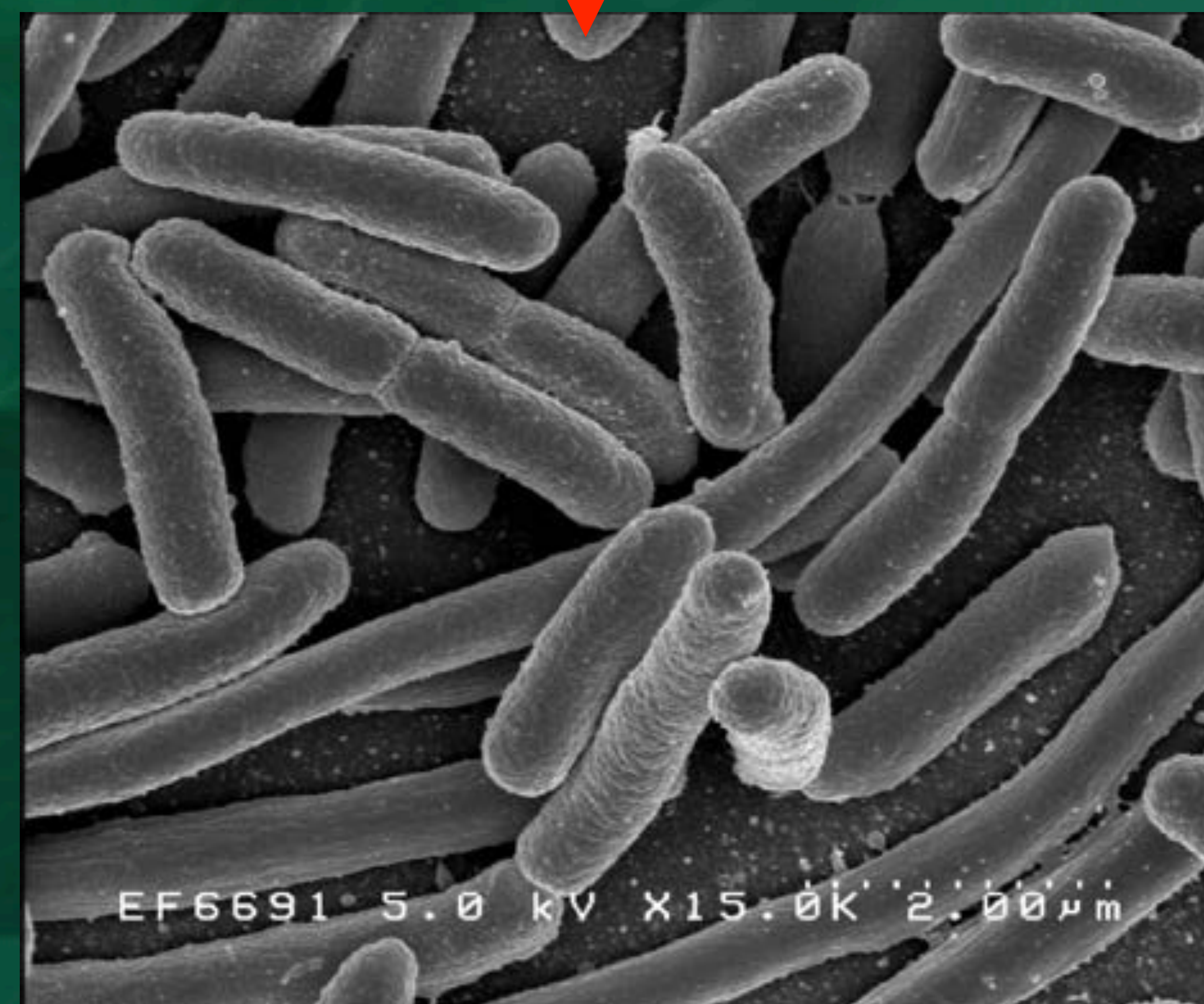
Omnis cellula e cellula.

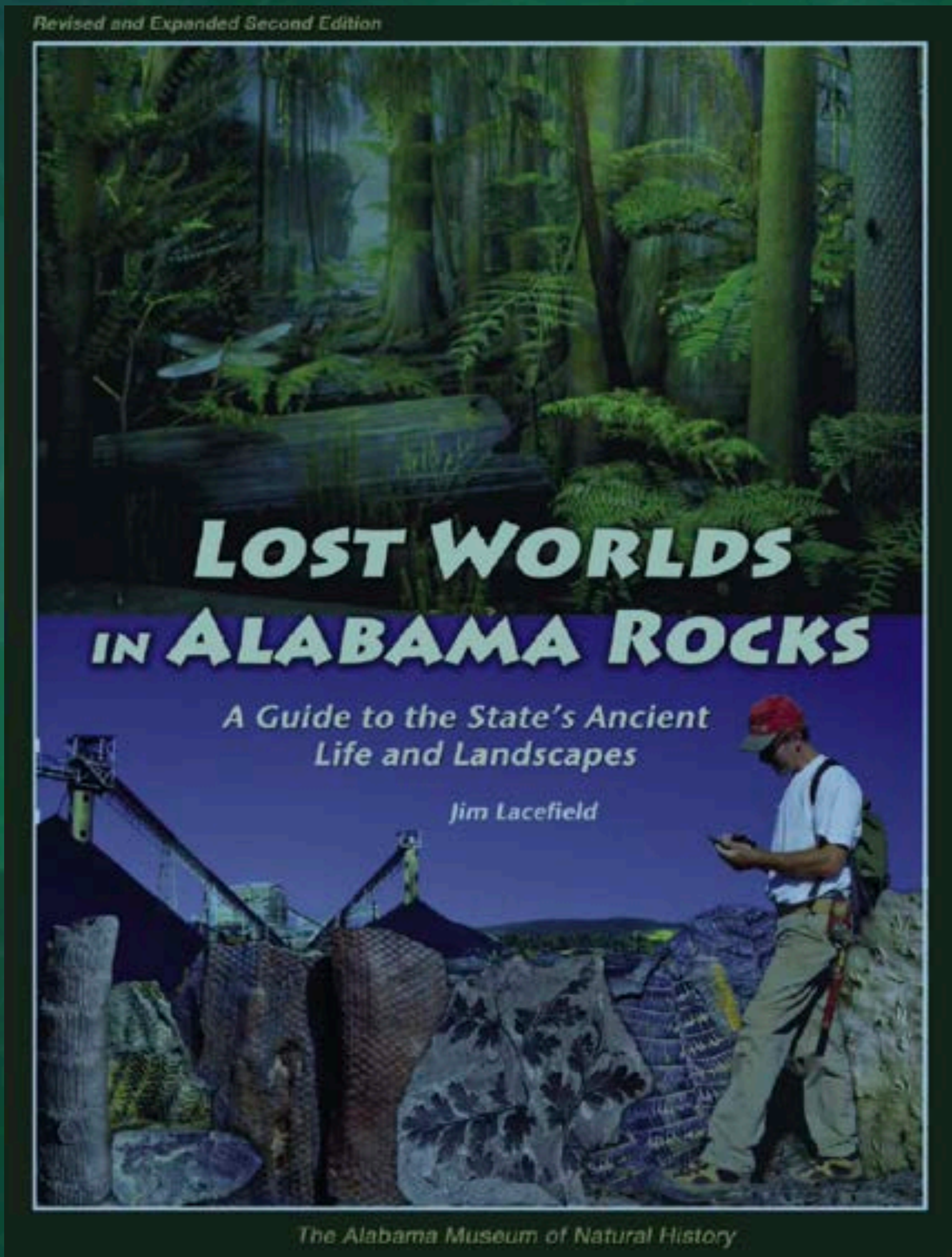
Every cell comes from a preexistent cell.

Omnis cellula e cellula



Every cell is contained by a <u>bilayer lipid membrane</u>, which separates the *aqueous <u>living system</u>* <u>inside</u> from the *aqueous environment* outside.

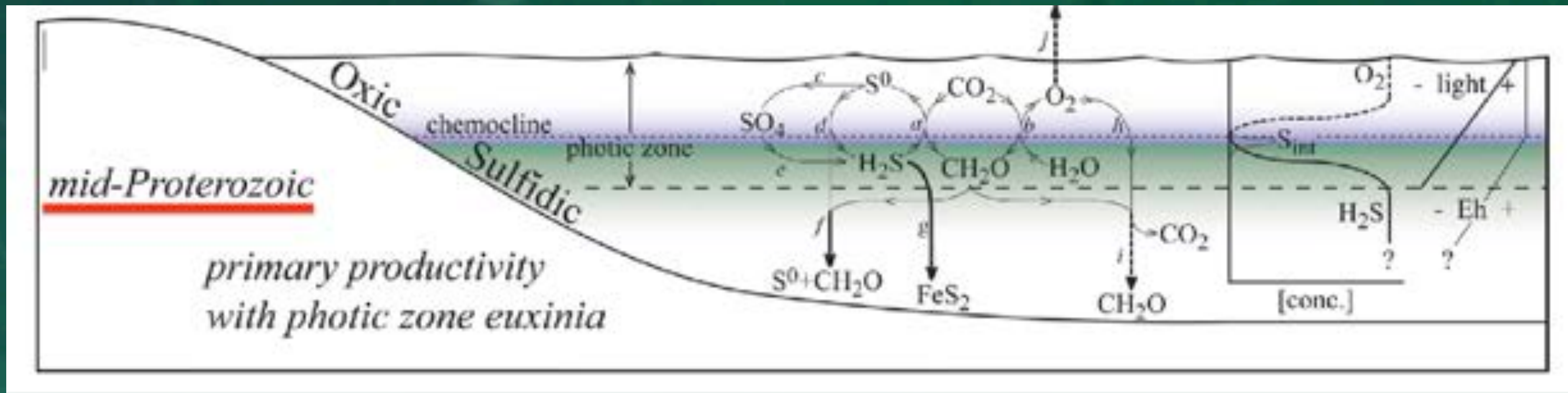




c. 2013

A Timetable of Alabama Geologic History

Era	Time Period	When Began (in millions of years)	Epoch	Significant Events in Alabama's Geologic History
Cenozoic Era	Quaternary	10,000 years	Holocene	our present epoch of Earth history
Cenozoic Era	Quaternary	2.6	Pleistocene	the "Ice Age"; Alabama ecosystems unlike today—northern tree species, megafauna
Cenozoic Era	Tertiary Period	5	Pliocene	Alabama landscape undergoes slight uplift, deep erosion of uplands
Cenozoic Era	Tertiary Period	23	Miocene	Earth's climate becomes unstable; fossil pollen studies show deciduous trees start to dominate Alabama forests
Cenozoic Era	Tertiary Period	34	Oligocene	
Cenozoic Era	Epochs →	56	Eocene	Alabama climate warm and wet, forests still contain many tropical tree species; lignite coal forms in Gulf coastal marshes
Cenozoic Era		65	Paleocene	
Mesozoic Era	Cretaceous	146		sea levels very high, warm oceans cover most of Alabama; "Selma chalk" forms offshore; dinosaurs roam tropical jungles
Mesozoic Era	Jurassic	200		opening of the Gulf of Mexico; Alabama climate still hot and dry; rich oil deposits form along edge of young, expanding Gulf
Mesozoic Era	Triassic	251		supercontinent of Pangaea begins to rift apart; Alabama moves north of the equator; state's climate and landscape desert-like
Paleozoic Era	Permian	299		probable peak of Appalachian Mtn. formation, Alabama locked within dry interior of Pangaea, no rocks from this time known from the state
Paleozoic Era	Carboniferous	318	Pennsylvanian	"Coal Age" forests; Pangaea forms
Paleozoic Era	Carboniferous	359	Mississippian	widespread limestones deposited
Paleozoic Era	Devonian	416		sometimes called the "age of fishes", but land plants and animals also diversify and move farther from the water's edge
Paleozoic Era	Silurian	444		Birmingham's Red Mountain iron ores form; terrestrial (land) environments first invaded by plants and animals
Paleozoic Era	Ordovician	488		tropical seas cover most of the state; Alabama rocks show mountain-building, volcanic activity was nearby to the east
Paleozoic Era	Cambrian Period	542 million years ago		Alabama on passive margin of ancient North American continent Laurentia; earliest fossils appear in Alabama rocks
"Precambrian"	"Precambrian" (represents about 87% of the Earth's history)			first multicellular organisms appear in the fossil record
"Precambrian"				Grenville mountain-building episode; deep crust beneath Alabama added
"Precambrian"	Proterozoic Eon	2.5 billion		first "free" oxygen accumulates in the Earth's atmosphere
"Precambrian"	Archaean Eon	3.8 billion		earliest fossilized bacteria appear in the geologic record
"Precambrian"		4 billion		age of Earth's oldest known rocks



Anoxygenic photosynthesis modulated Proterozoic oxygen and sustained Earth's middle age

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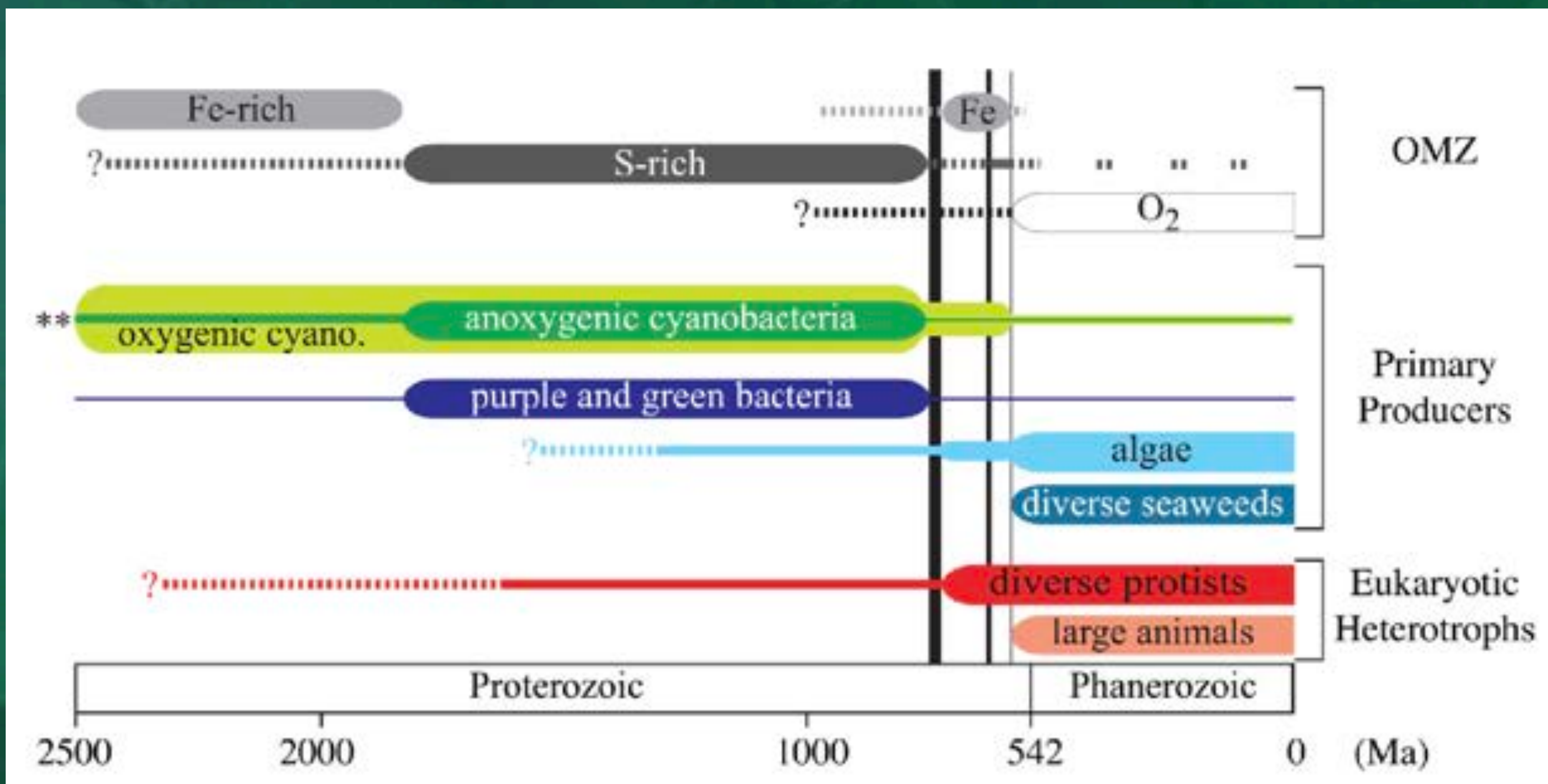
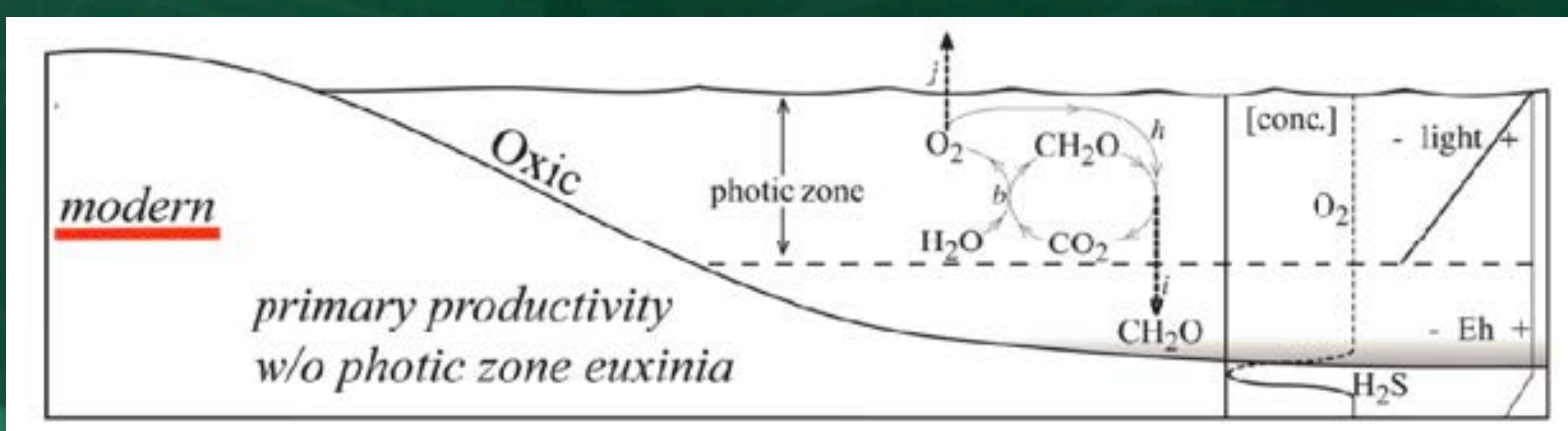
Contributed by A. H. Knoll, August 14, 2009 (sent for review January 6, 2009)

PNAS - 2009



Molecular oxygen (O_2) began to accumulate in the atmosphere and surface ocean ca. 2,400 million years ago (Ma), but the persistent oxygenation of water masses throughout the oceans developed much later, perhaps beginning as recently as 580–550 Ma. For much of the intervening interval, moderately oxic surface waters lay above an oxygen minimum zone (OMZ) that tended toward euxinia (anoxic and sulfidic). Here we illustrate how contributions to primary production by anoxygenic photoautotrophs (including physiologically versatile cyanobacteria) influenced biogeochemical cycling during Earth's middle age, helping to perpetuate our planet's intermediate redox state by tempering O_2 production. Specifically, the ability to generate organic matter (OM) using sulfide as an electron donor enabled a positive biogeochemical feedback that sustained euxinia in the OMZ. On a geologic time scale, pyrite precipitation and burial governed a second feedback that moderated sulfide availability and water column oxygenation. Thus, we argue that the proportional contribution of anoxygenic photosynthesis to overall primary production would have influenced oceanic redox and the Proterozoic O_2 budget. Later Neoproterozoic collapse of widespread euxinia and a concomitant return to ferruginous (anoxic and Fe^{2+} rich) subsurface waters set in motion Earth's transition from its prokaryote-dominated middle age, removing a physiological barrier to eukaryotic diversification (sulfide) and establishing, for the first time in Earth's history, complete dominance of oxygenic photosynthesis in the oceans. This paved the way for the further oxygenation of the oceans and atmosphere and, ultimately, the evolution of complex multicellular organisms.



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Compr Physiol. 2013 April ; 3(2): 849–915. doi:10.1002/cphy.c120003.

Evolution of Air Breathing: Oxygen Homeostasis and the Transitions from Water to Land and Sky

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Abstract

Life originated in anoxia, but many organisms came to depend upon oxygen for survival, independently evolving diverse respiratory systems for acquiring oxygen from the environment. Ambient oxygen tension (PO_2) fluctuated through the ages in correlation with biodiversity and body size, enabling organisms to migrate from water to land and air and sometimes in the opposite direction. Habitat expansion compels the use of different gas exchangers, for example, skin, gills, tracheae, lungs, and their intermediate stages, that may coexist within the same species; coexistence may be temporally disjunct (e.g., larval gills vs. adult lungs) or simultaneous (e.g., skin, gills, and lungs in some salamanders). Disparate systems exhibit similar directions of adaptation: toward larger diffusion interfaces, thinner barriers, finer dynamic regulation, and reduced cost of breathing. Efficient respiratory gas exchange, coupled to downstream convective and diffusive resistances, comprise the "oxygen cascade"—step-down of PO_2 that balances supply against toxicity. Here, we review the origin of oxygen homeostasis, a primal selection factor for all respiratory systems, which in turn function as gatekeepers of the cascade. Within an organism's lifespan, the respiratory apparatus adapts in various ways to upregulate oxygen uptake in hypoxia and restrict uptake in hyperoxia. In an evolutionary context, certain species also become adapted to environmental conditions or habitual organismic demands. We, therefore, survey the comparative anatomy and physiology of respiratory systems from invertebrates to vertebrates, water to air breathers, and terrestrial to aerial inhabitants. Through the evolutionary directions and variety of gas exchangers, their shared features and individual compromises may be appreciated.

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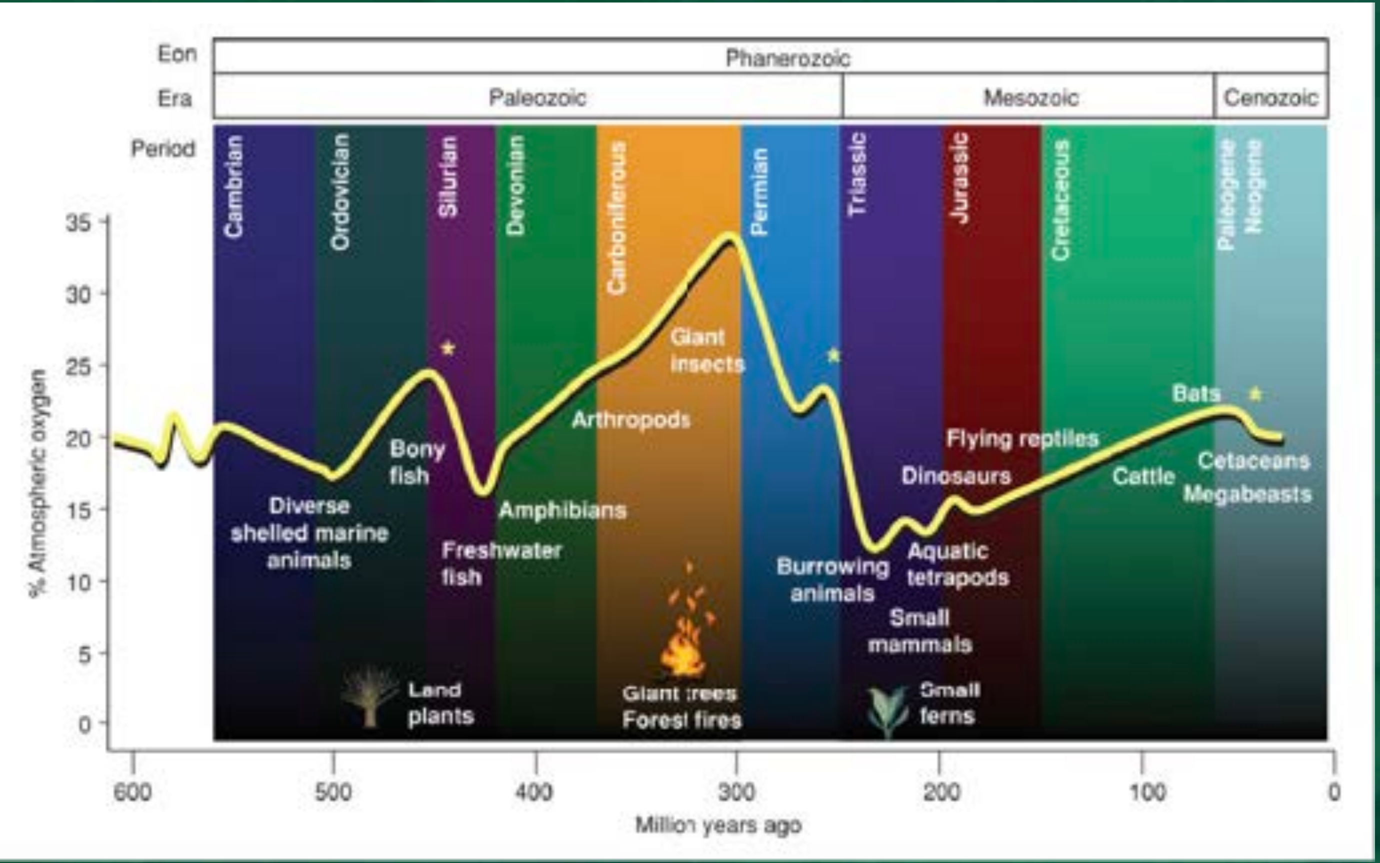
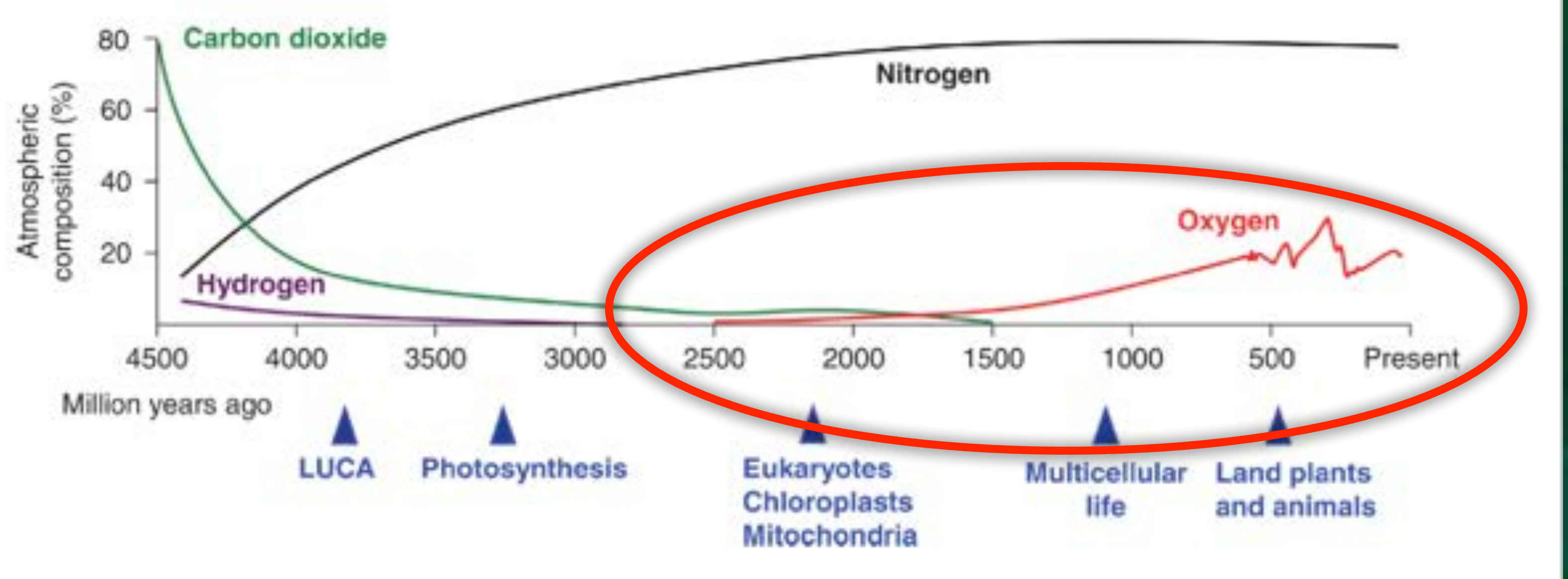


Hsia et al.



STROMATOLITES: Interaction of Microbes with Sediments

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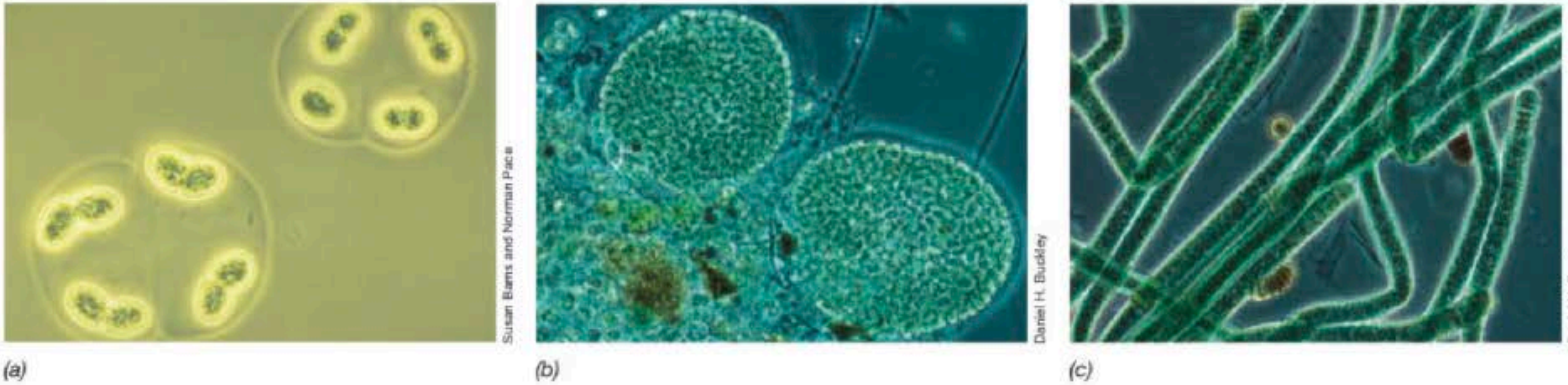

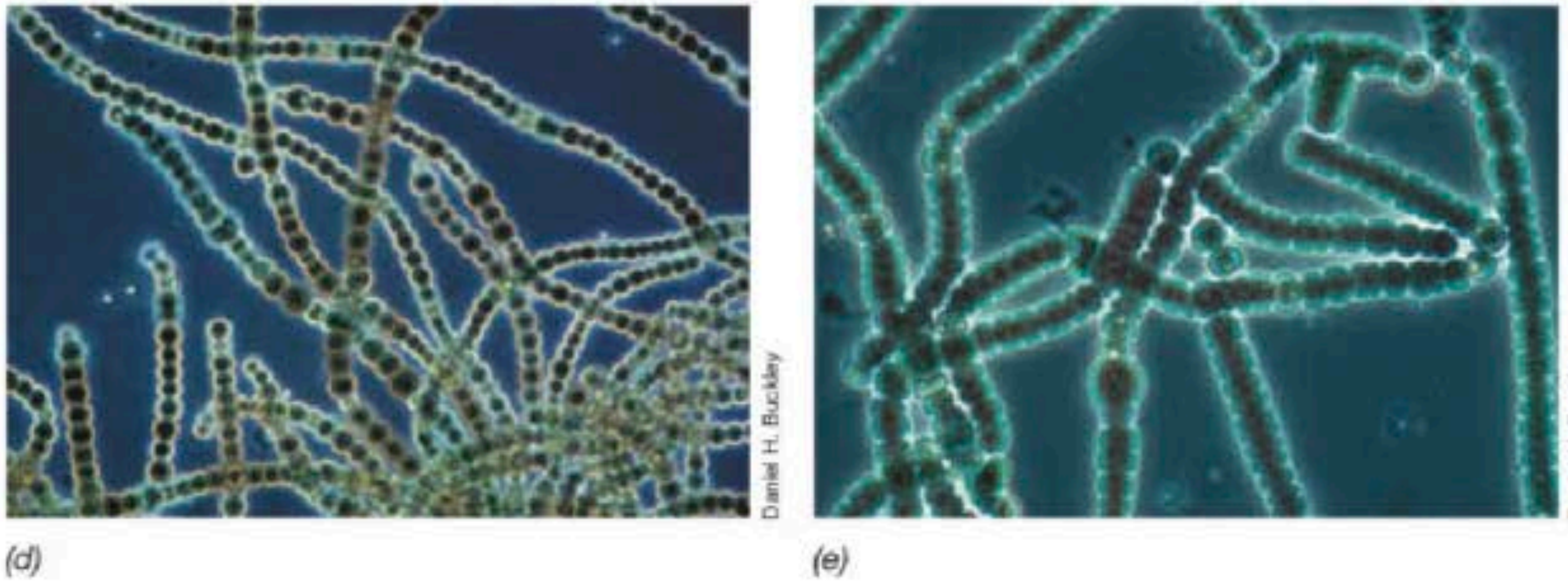

Figure 15.2 The five major morphological types of *Cyanobacteria*. *(a)* Unicellular, *Gloeothece*; a single cell measures 5–6 µm in diameter; *(b)* colonial, *Pleurocapsa*; these structures are >50 µm in diameter and contain hundreds of cells; *(c)* filamentous, *Lyngbya*; a single cell measures about 10 µm wide; *(d)* filamentous heterocystous, *Nodularia*; a single cell measures about 10 µm wide; *(e)* filamentous branching, *Fischerella*; a cell is about 10 µm wide. See how morphological diversity relates to phylogenetic diversity in Figure 15.3.

Cyanobacteria are photosynthetic organisms responsible for ~25% of the organic carbon fixation on earth.

A key step in carbon fixation is catalyzed by ribulose bisphosphate carboxylase/ oxygenase

RuBisCO - *the most abundant enzyme on the planet*

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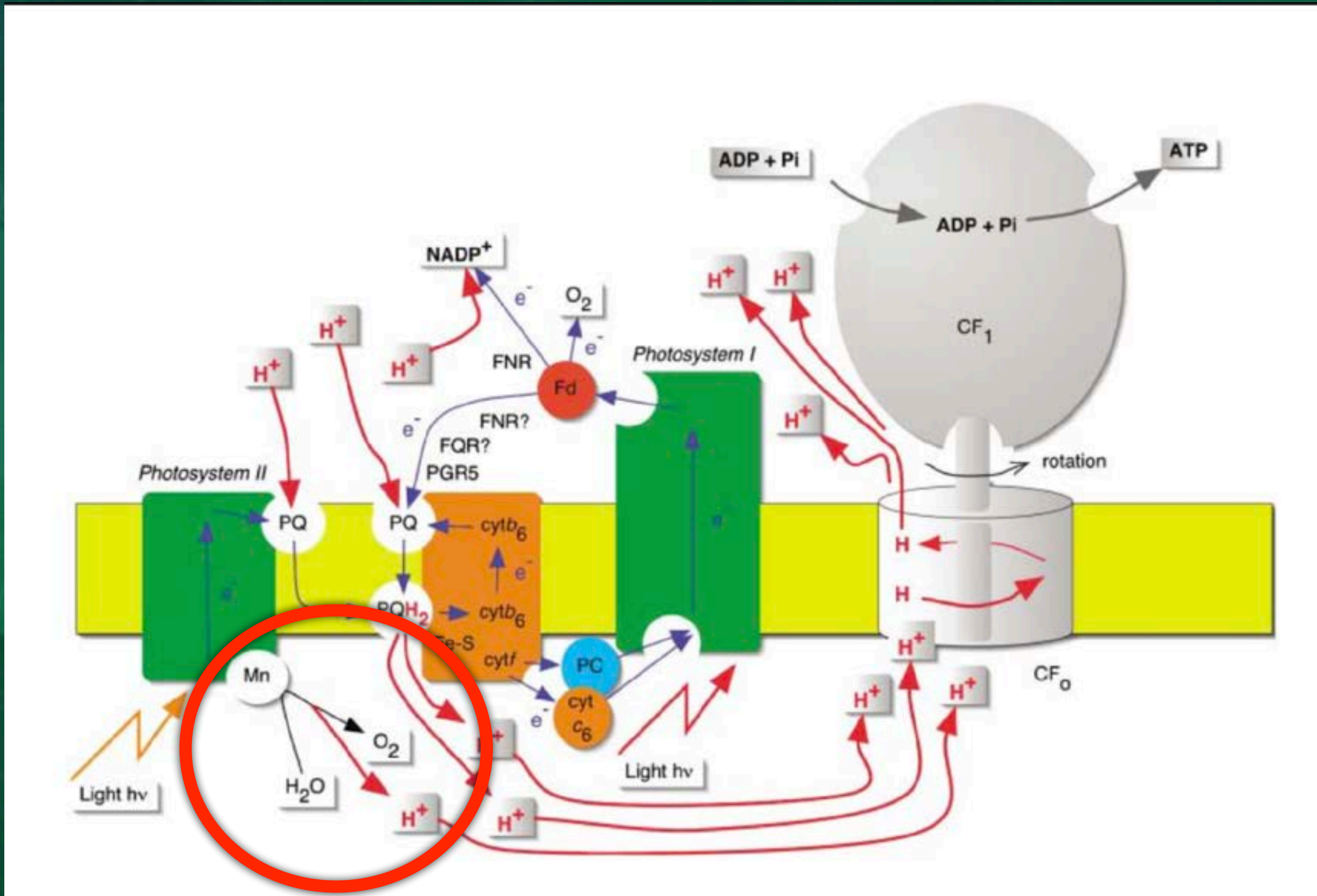
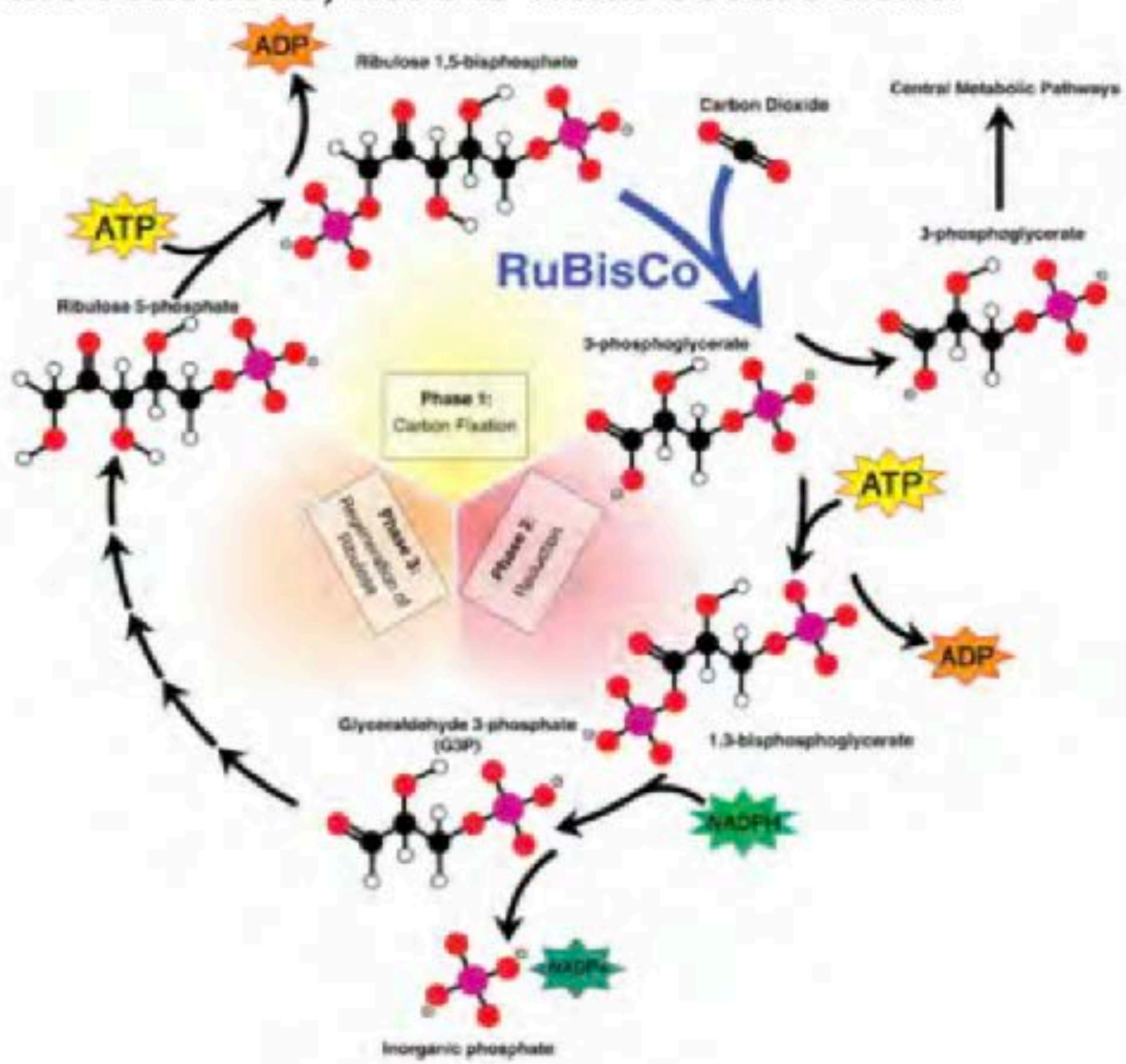

ADP + Pi
ATP
ADP + Pi
NADP+
H+
H+
e-
O2
CF1
H+
H+
e-
FNR
Photosystem I
H+
H+
Fd
H+
e-
FNR?
FQR?
PGR5
Photosystem II
rotation
PQ
PQ
cytb6
e-
H
cytb6
H
Mn
cytf
PC
H+
CFo
O2
cyt c6
H+
H+
Light hν
H2O
Light hν
H+
H+

With **ATP** available to drive the reactions, here is what occurs next:



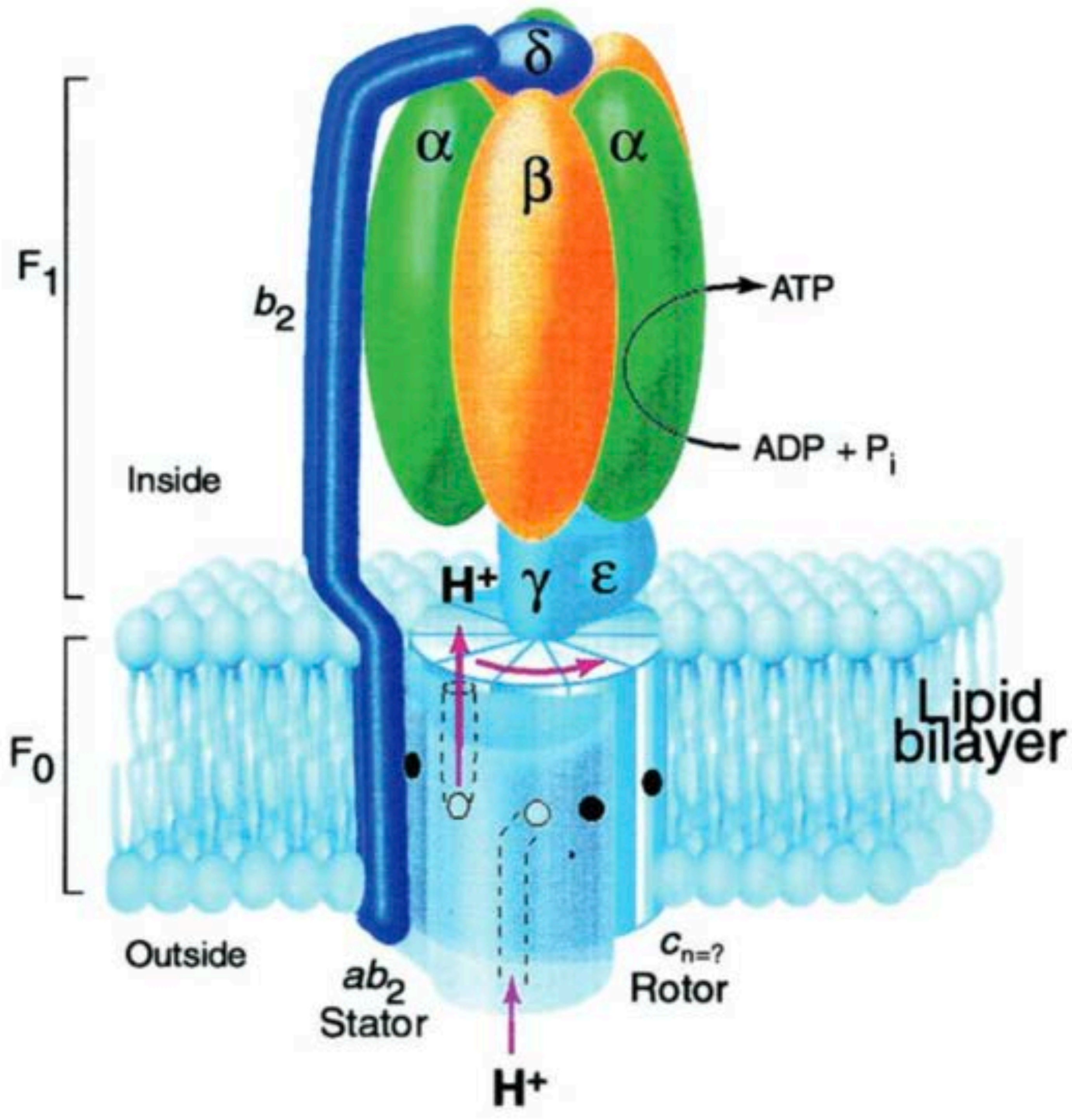


FIG. 7. The components of ATP synthase, a rotary motor. Protons enter the 10 proton channels in the membrane-bound F_o component, where they bind to Asp^{61}, and are subsequently released to the opposite side of the membrane via an outlet channel after F_o rotation (arrow). The γε-subunits are attached to the F_o ring and also rotate relative to the F_1 component, which catalyzes ATP synthesis (or breakdown if the reaction is driven backwards), which is thus driven by the proton-motive force. [From Jiang et al. (495), copyright 2001 National Academy of Sciences, USA.]

mitochondrial membrane proton pump: making ATP - 2 min. Harvard video

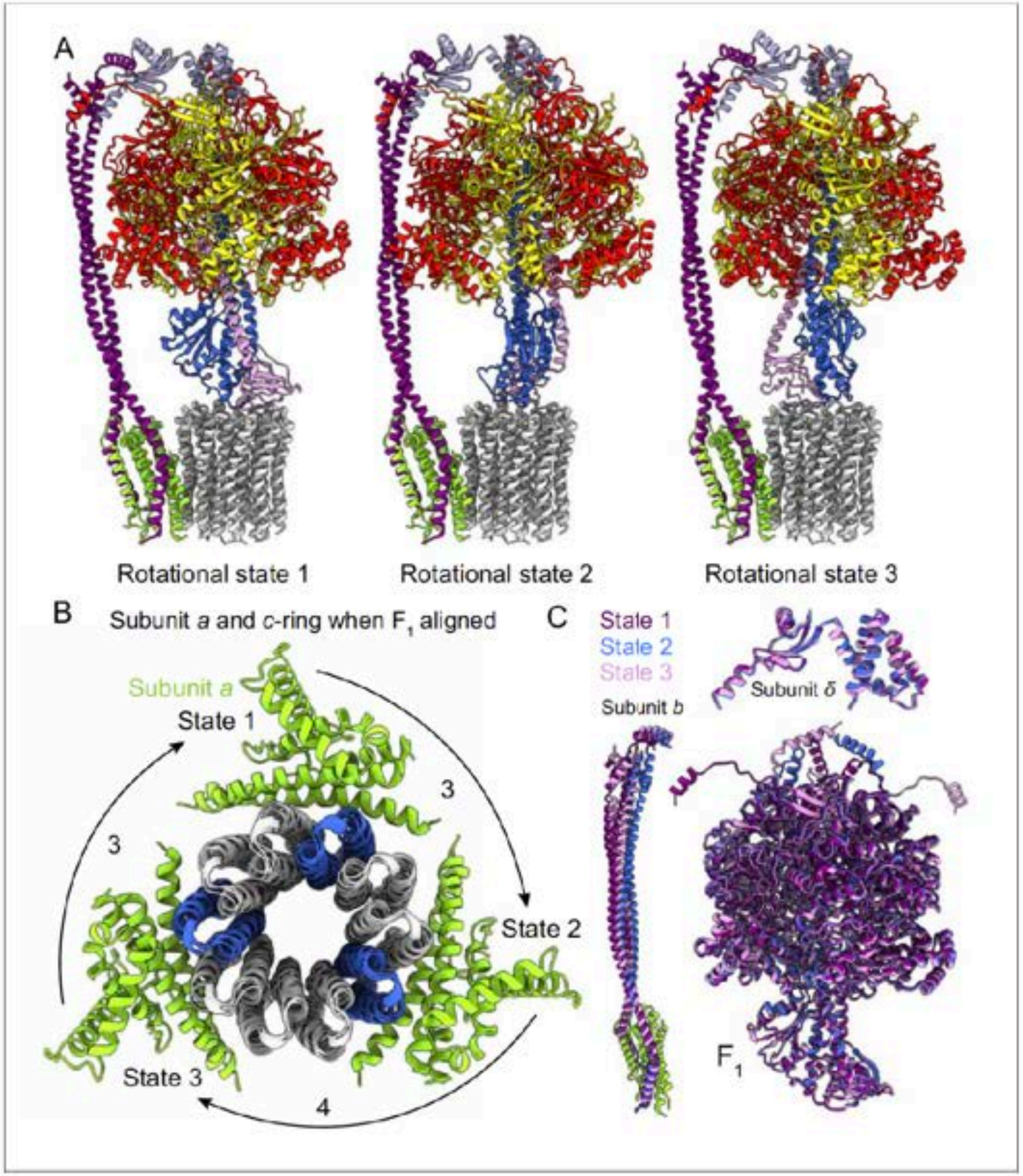


Figure 2. Rotational states of ATP synthase. (A) Atomic models of the three rotational states of *Bacillus* PS3 ATP synthase with subunits coloured the same as in *Figure 1*. (B) Top view of the c-ring and subunit *a* of the three rotational states from the cytoplasm when the F_1 regions of the three states are aligned. Rotation steps of the complex between states are -3, 4, and 3 c-subunits. (C) Comparison of the atomic models of subunits *b*, δ, and other F_1 region subunits in the different rotational states. The *b* subunits appear to be the most flexible part of the enzyme.

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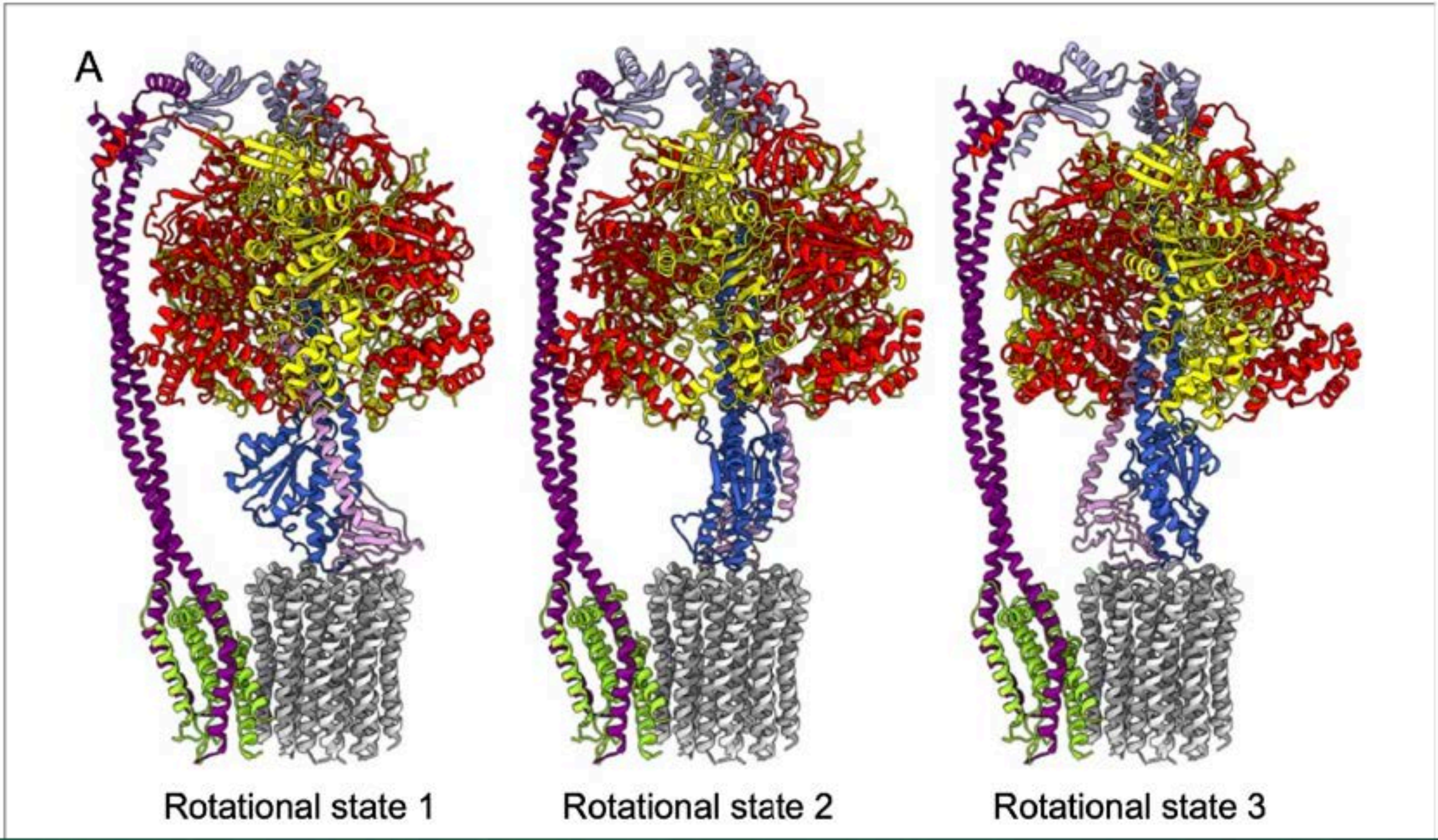

A
Rotational state 1
Rotational state 2
Rotational state 3

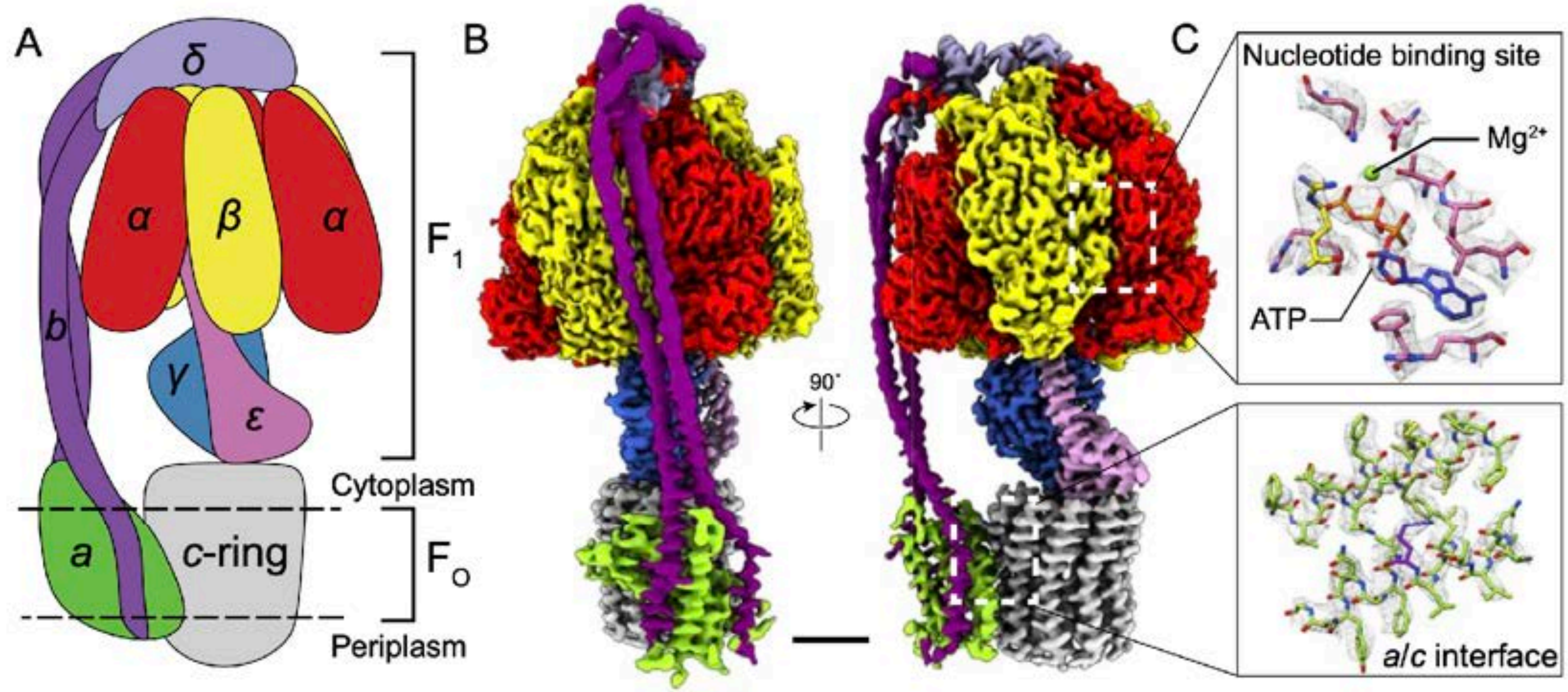


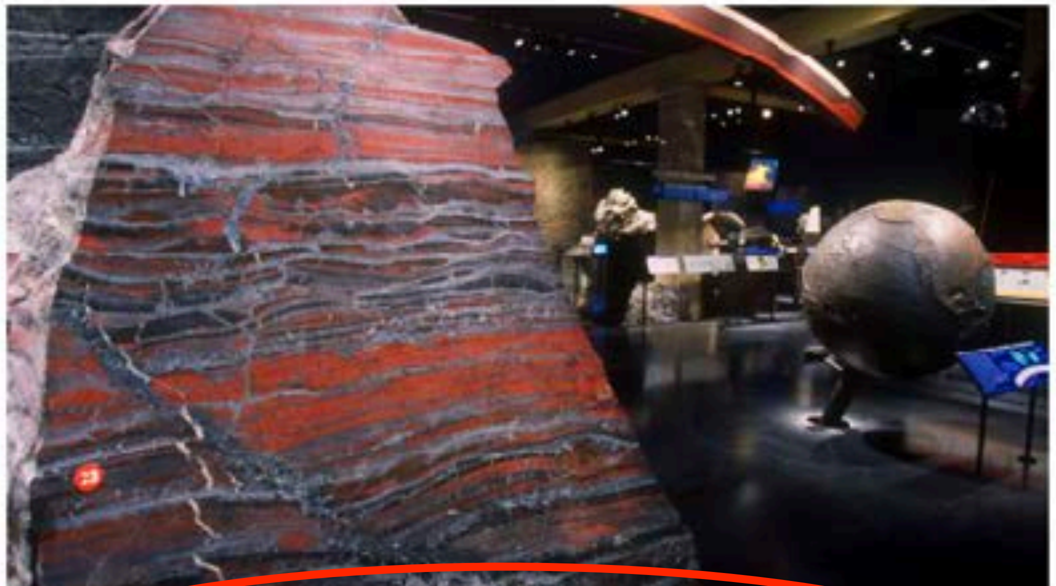
Figure 1. Overall structure of *Bacillus* PS3 ATP synthase. (**A**) Cartoon of ATP synthase. (**B**) Cryo-EM map of ATP synthase with subunits coloured the same as the cartoon. (**C**) Example map density that allowed construction of an atomic model. Scale bar, 30 Å.

DOI: https://doi.org/10.7554/eLife.43128.002

American Museum *of* Natural History

Banded Iron Formation

Part of Hall of Planet Earth

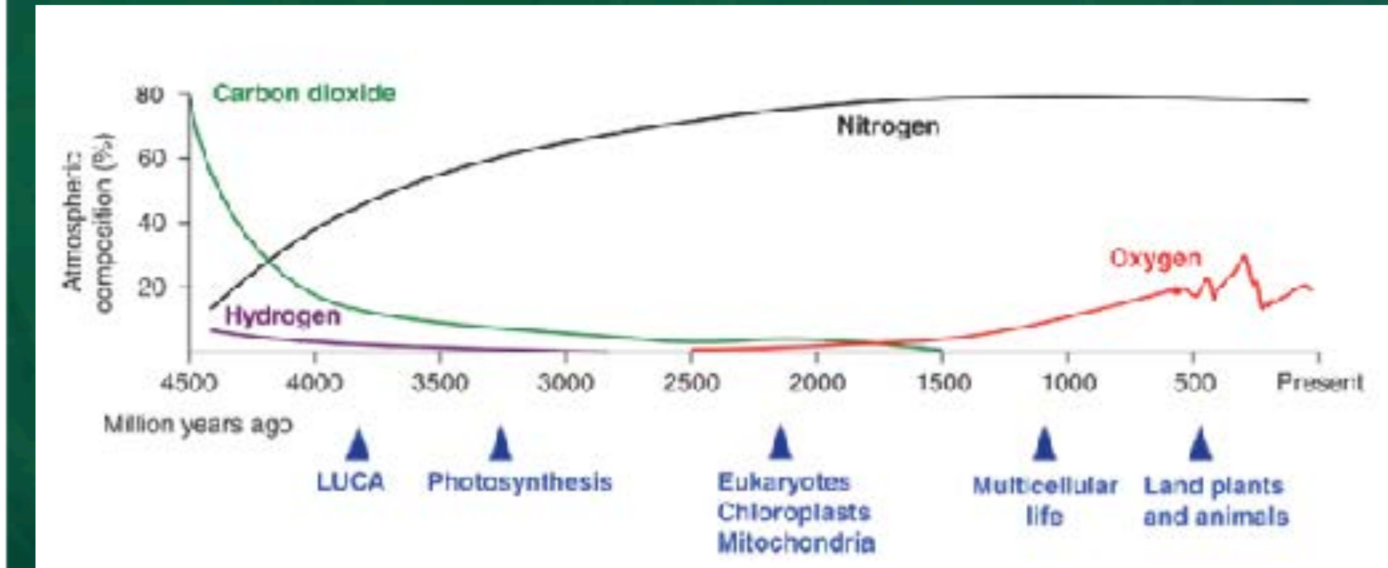


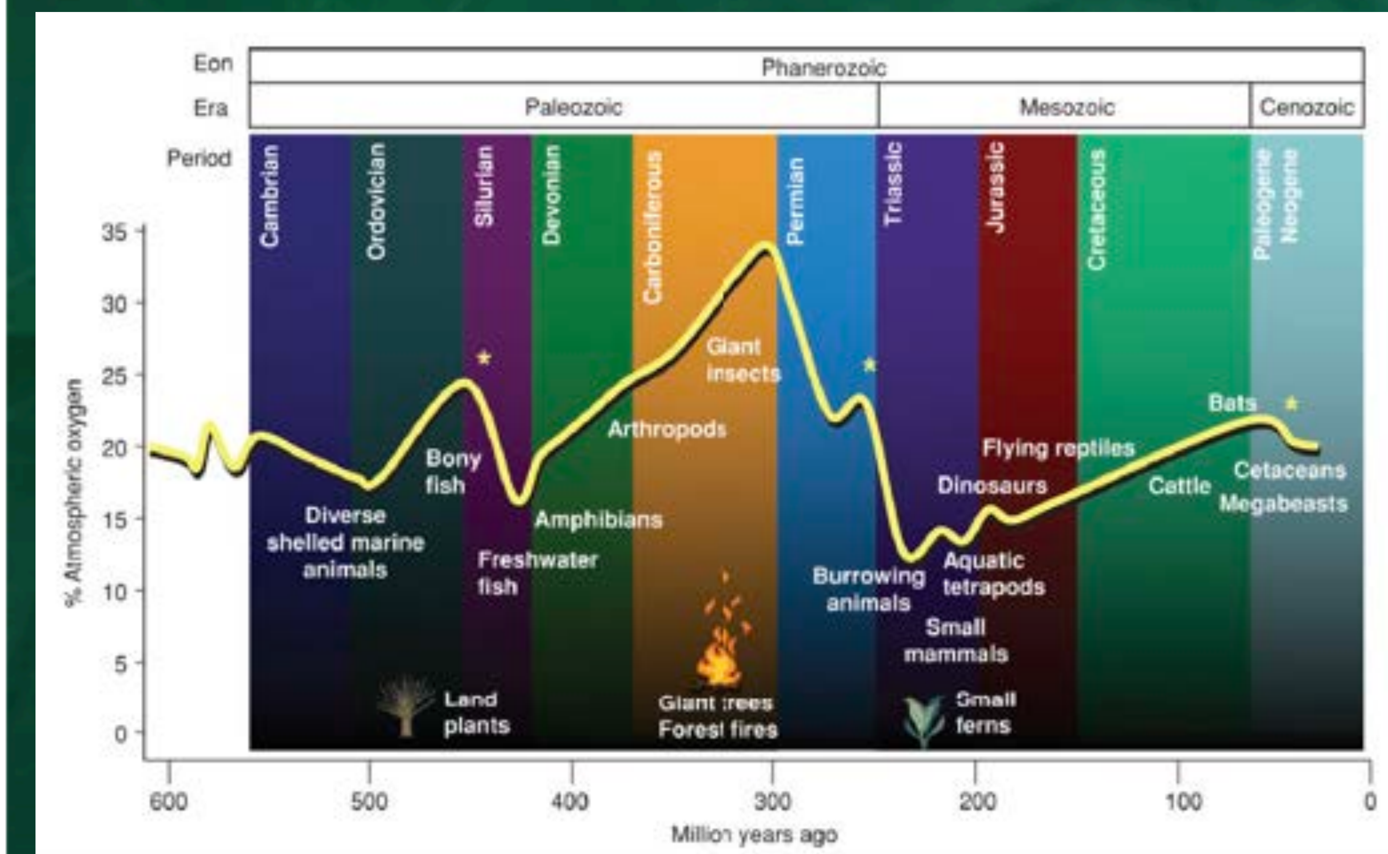
A nearly 3-billion-year-old banded iron formation from Canada shows that the atmosphere and ocean once had no oxygen.

Photosynthetic organisms were making oxygen, but it reacted with the iron dissolved in seawater to form iron oxide minerals on the ocean floor, creating banded iron formations.

The dark layers in this boulder are mainly composed of magnetite (Fe_3O_4) while the red layers are chalcedony, a form of silica (SiO_2) that is colored red by tiny iron oxide particles. Some geologists suggest that the layers formed annually with the changing seasons.

This rock records a time from the Earth's distant past, when evolving life profoundly influenced the planet's evolution. The oxygen that is now in the Earth's atmosphere was not there at the beginning. Early life began to generate oxygen by converting the Sun's energy into food. That caused the iron that was dissolved in the oceans to precipitate out as iron oxide minerals. This rock, with its layers of red jasper and iron magnetite, was formed billions of years ago as part of that process. It is a reminder that life made our atmosphere breathable.





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Banded Iron Formation (BIF)

Early Proterozoic probably from near Marquette in the Upper Peninsula of Michigan; red quartz layers and black layers of specular hematite and magnetite. The layering is though to be produced biannually in shallow seas. In general, banded iron formations of the oxide-carbonate-silicate-sulphide type occur in Archean greenstone belts and reached their peak development in the early Proterozoic basins about 2000-1800 Ma ago. Mid-late Proterozoic and Phanerozoic basins do not contain BIF of this type. In contrast, iron formations containing chamosite-goethite-siderite are unknown in the Precambrian but are found in Phanerozoic basins. The occurrence of the Precambrian BIF's is thought to be related to anoxic conditions of the early atmosphere. As oxygen content of the atmosphere and ocean waters increased, the solubility of iron decreased. With these changes in solubility, transport of iron in the entire weathering cycle would have decreased. Iron would remain in soils and not be found in solution in ocean waters after the atmosphere became oxygen-rich.

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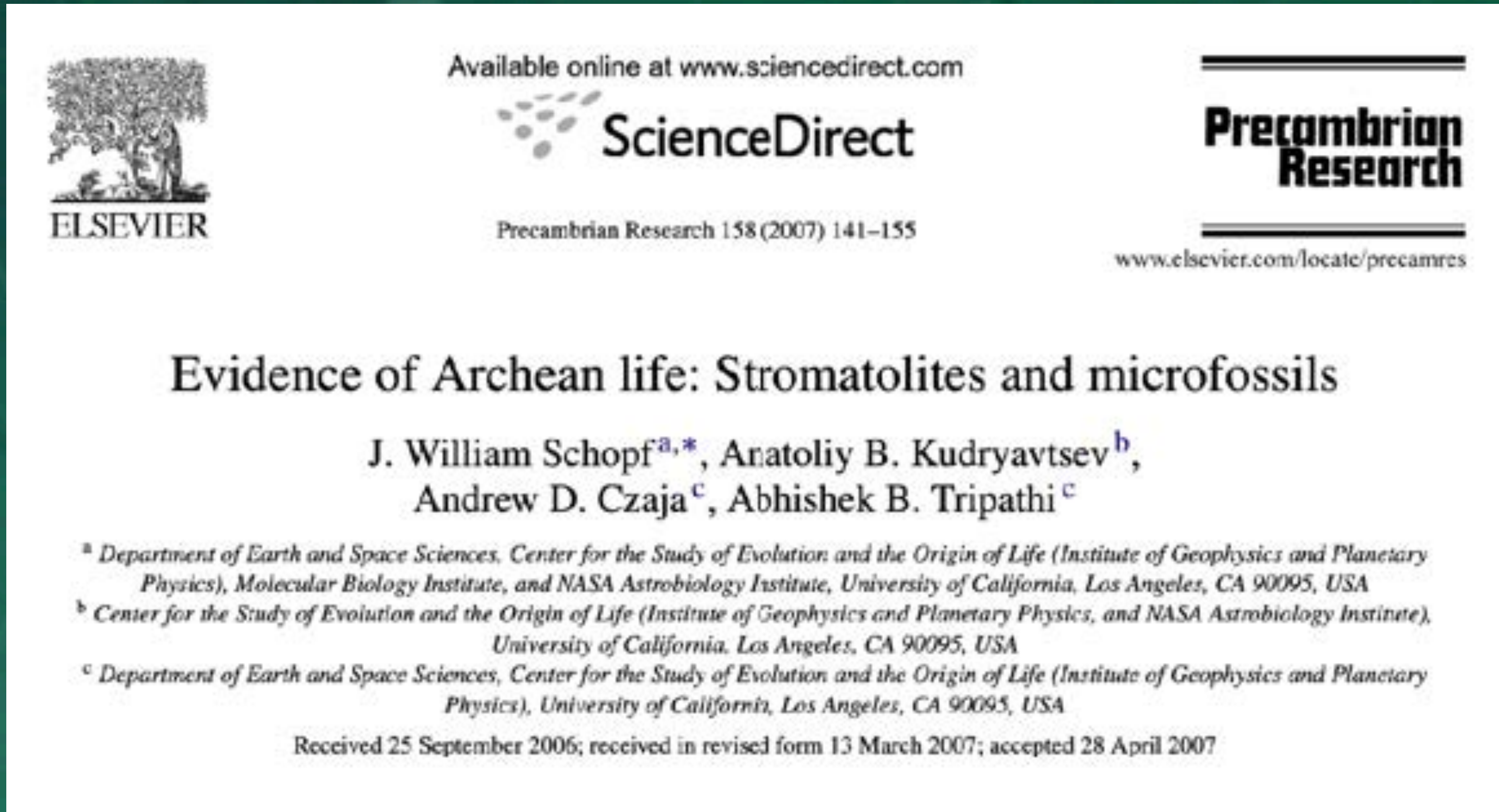
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Precambrian Research 158 (2007) 141–155
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Evidence of Archean life: Stromatolites and microfossils

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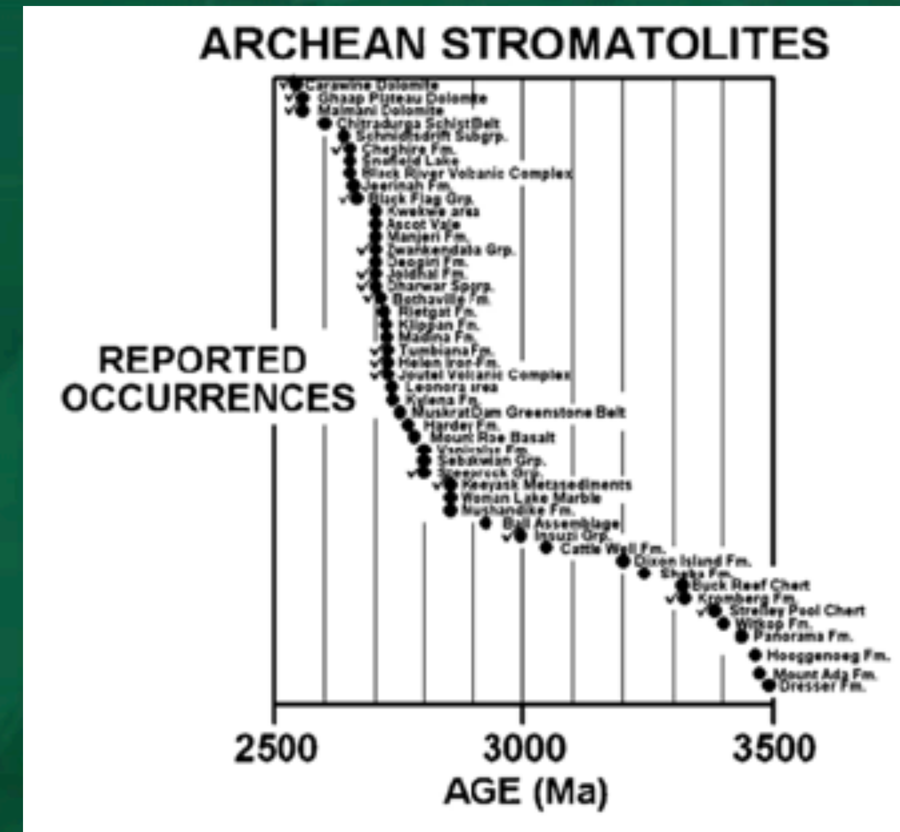

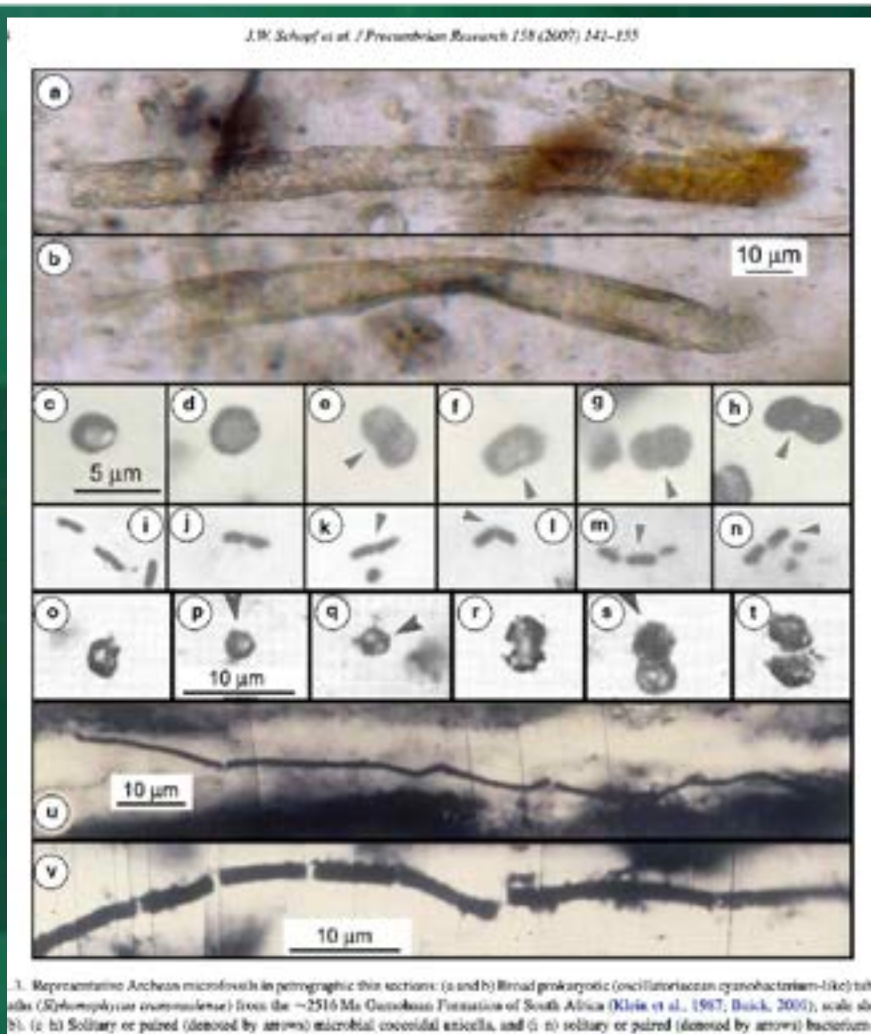

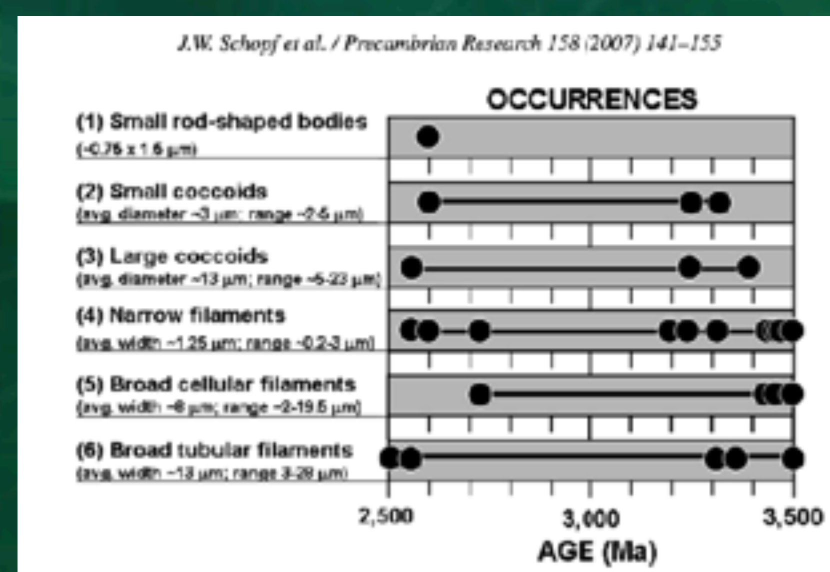

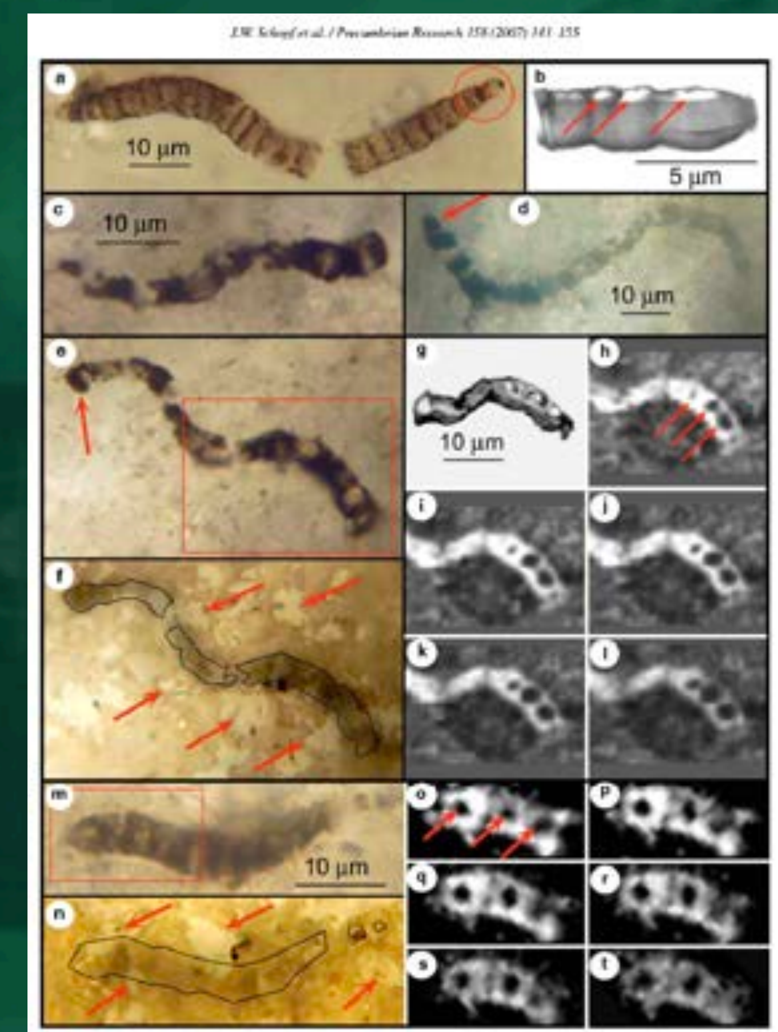

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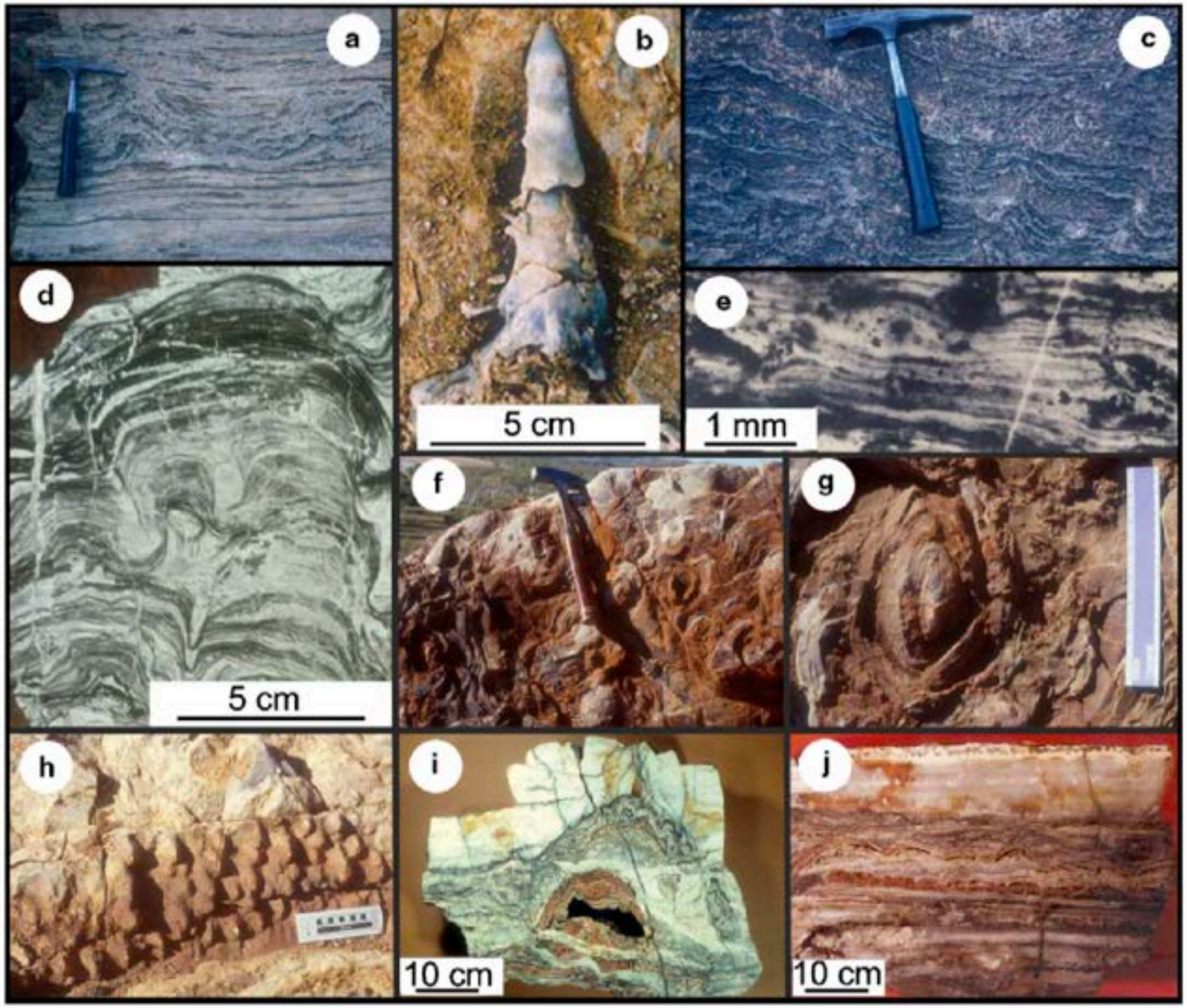

Fig. 2. Representative Archean stromatolites: (a–c) Stratiform and conical stromatolites from the ~2985 Ma Insuzi Group, South Africa (Beukes and Lowe, 1989); photo in (b) courtesy of N.J. Beukes. (d) Laterally linked, low relief stratiform to domical stromatolitic mats from the ~3245 Ma Fig Tree Group of South Africa (Byerly et al., 1986); photo courtesy of D.R. Lowe. (e) Stratiform microbial mats from the ~3320 Ma Kromberg Formation of South Africa (Walsh and Lowe, 1985). (f–h) Conical stromatolites from the ~3388 Ma Strelley Pool Chert of Western Australia (Hofmann et al., 1999; see also Allwood et al. 2007 of *Precambrian Research*, p. 198); scale in (g) = 20 cm; scale in (h) = 10 cm. (i) Domical and (j) stratiform stromatolites from the 3496 Ma Dresser Formation, Western Australia (Walter et al., 1980; Buick et al., 1981).

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Chemostratigraphy of Paleoproterozoic carbonate successions of the Wyoming Craton: tectonic forcing of biogeochemical change?

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Accepted 11 October 2002

Abstract

The Archean Wyoming Craton is flanked on the south and east by belts of Paleoproterozoic supracrustal successions whose correlation is complicated by lack of geochronologic constraints and continuous outcrop. However, carbonate units in these successions may be correlated by integrating carbon isotope stratigraphy with lithostratigraphy. The ~10 km thick Paleoproterozoic Snowy Pass Supergroup in the Medicine Bow Mountains was deposited on the present-day southern flank of the Wyoming Craton; it contains three discrete levels of glacial diamictite correlative with those in the Huronian Supergroup, on the southern margin of the Superior Craton. The Nash Fork Formation of the upper Snowy Pass Supergroup is significantly younger than the uppermost diamictite and was deposited after the end of the Paleoproterozoic glacial epoch. Carbonates at the base of the Nash Fork Formation record remarkable ^{13}C-enrichment, up to +28‰ (V-PDB), whereas those from overlying members of the lower Nash Fork Formation have $\delta^{13}C$ values between −6 and +8‰. Carbonates from the upper Nash Fork Formation above the carbonaceous shale have carbon isotope values ranging between 0 and +2.5‰. The transition from high carbon isotope values to those near 0‰ in the Nash Fork Formation is similar to that at the end of the ca. 2.2–2.1 Ga carbon isotope excursion in Fennoscandia. This chemostratigraphic trend and deposition of BIFs, Mn-rich lithologies, carbonaceous shales and phosphorites at the end of the global ca. 2.2–2.1 Ga carbon isotope excursion are likely related to ocean overturn associated with the final breakup of the Kenorland supercontinent. Correlative carbonates from the Slaughterhouse Formation in the Sierra Madre, WY, and from the Whalen Group in the Rawhide Creek area in the Hartville Uplift, WY, have highly positive carbon isotope values. In contrast, carbonates from other exposures of the Whalen Group in the Hartville Uplift and all carbonate units in the Black Hills, SD, have carbon isotope values close to 0‰. Combined with existing geochronologic and stratigraphic constraints, these data suggest that the Slaughterhouse Formation and the succession exposed in the Rawhide Creek area of the Hartville Uplift are correlative with the lower and middle Nash Fork Formation and were deposited during the ca. 2.2–2.1 Ga carbon isotope excursion. The Estes and Roberts Draw formations in the Black Hills and carbonates from other exposures in the Hartville Uplift postdate the ca. 2.2–2.1 Ga

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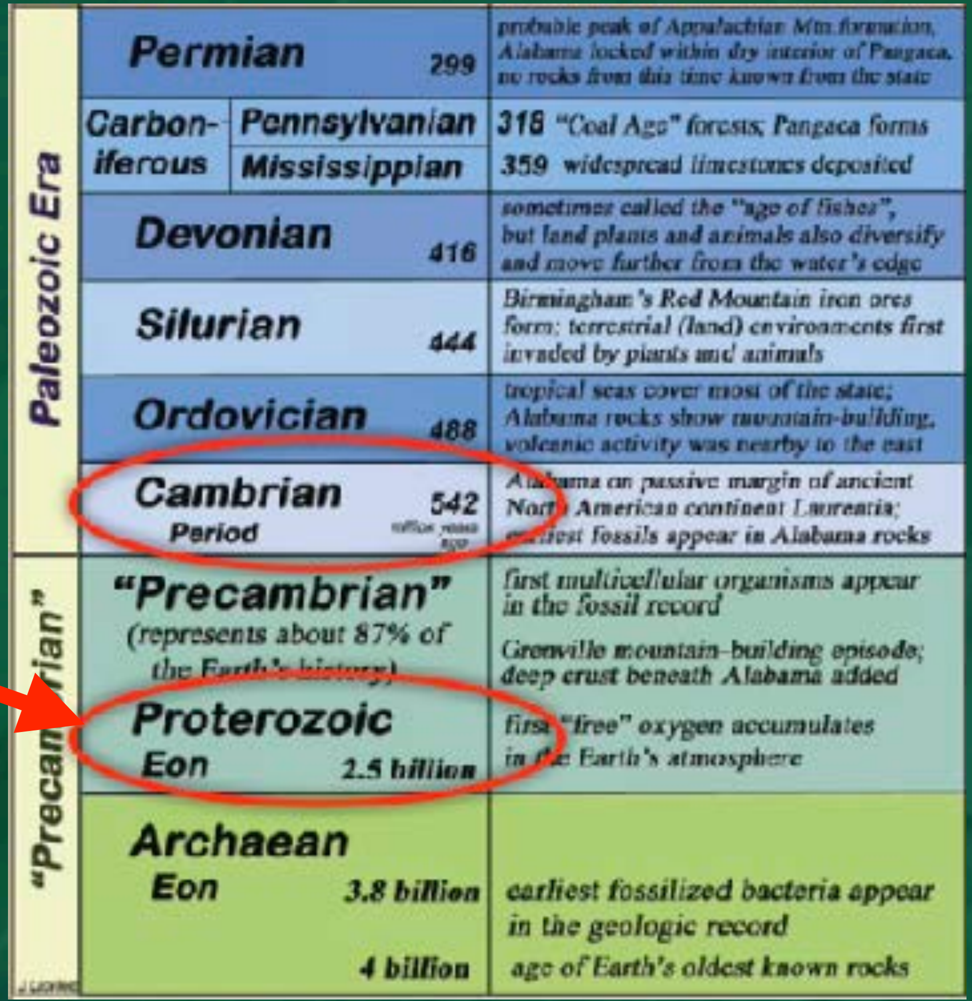


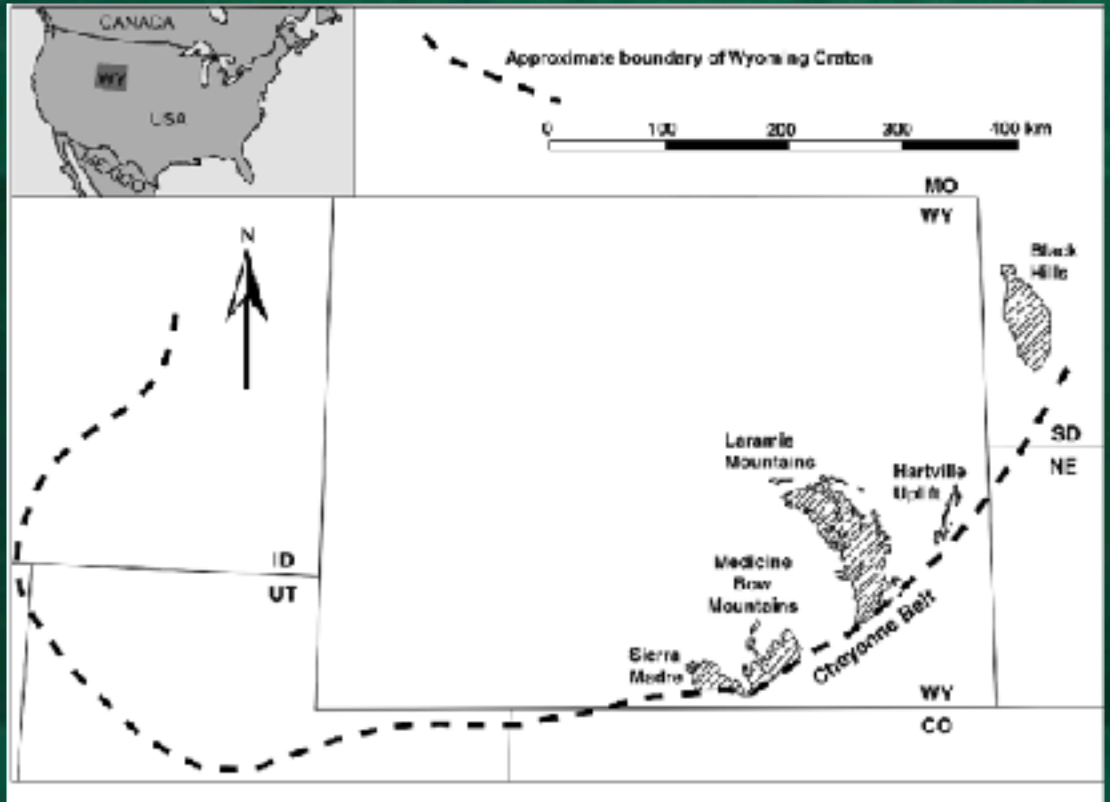


Fig. 1. Location of Paleoproterozoic sedimentary successions on the southeastern margin of the Wyoming Craton.

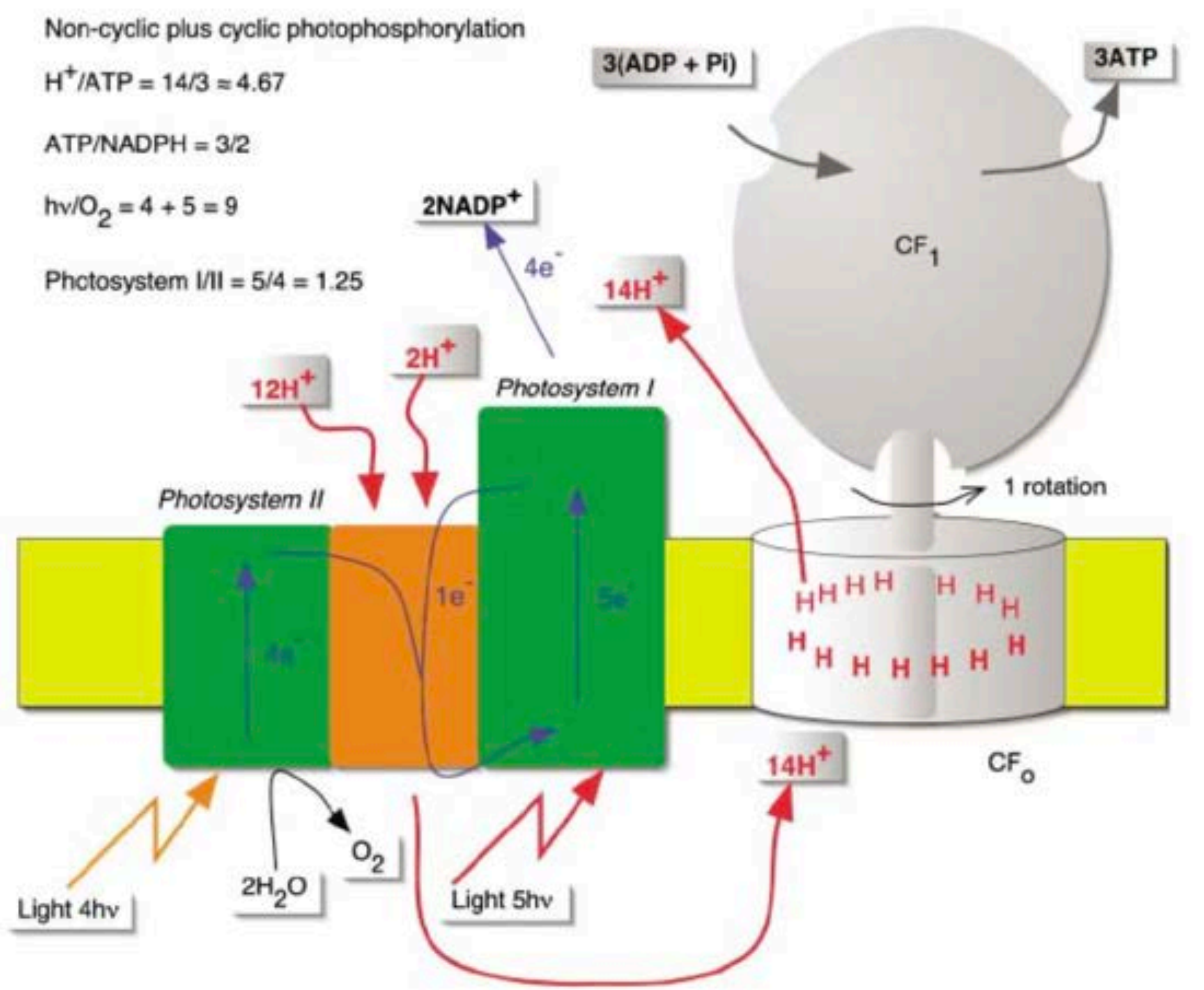
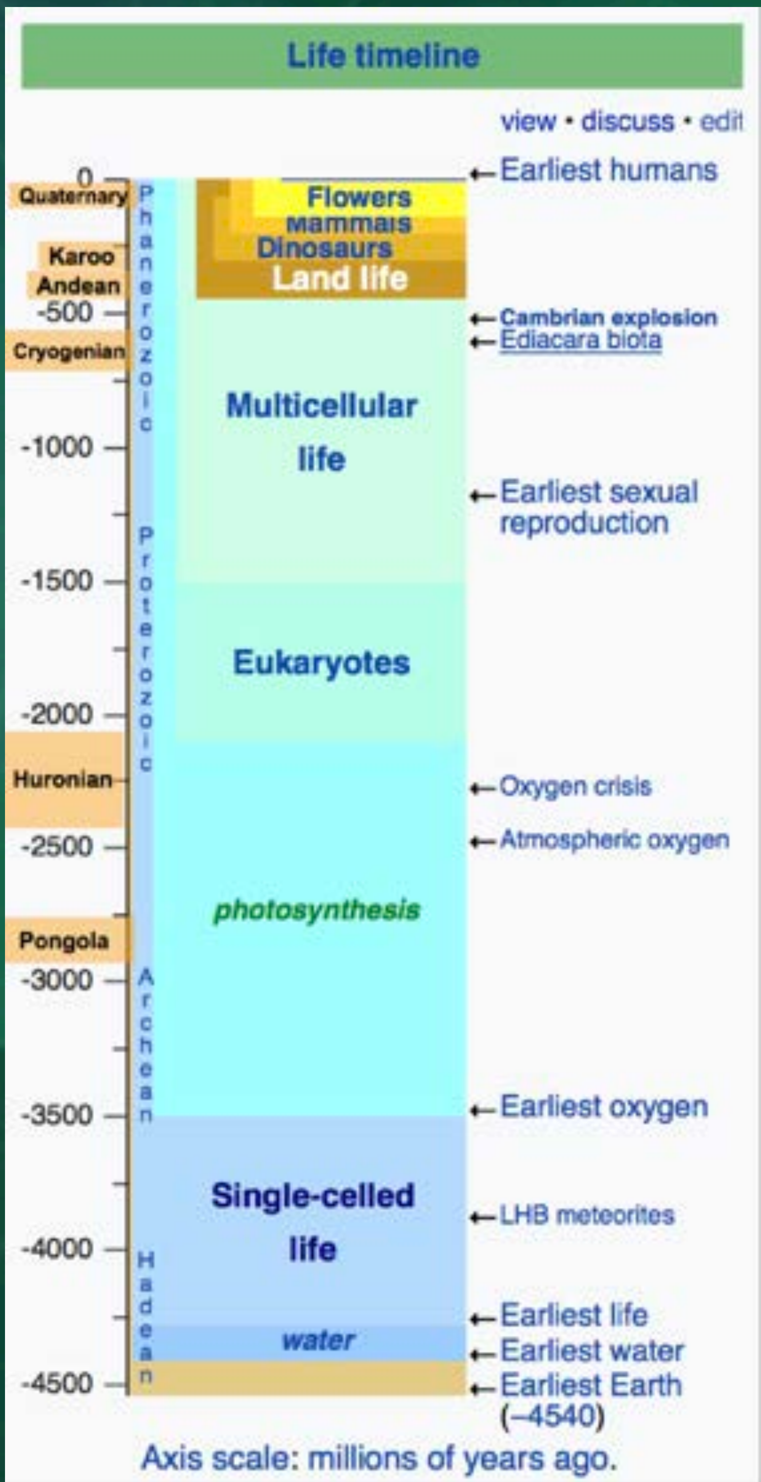
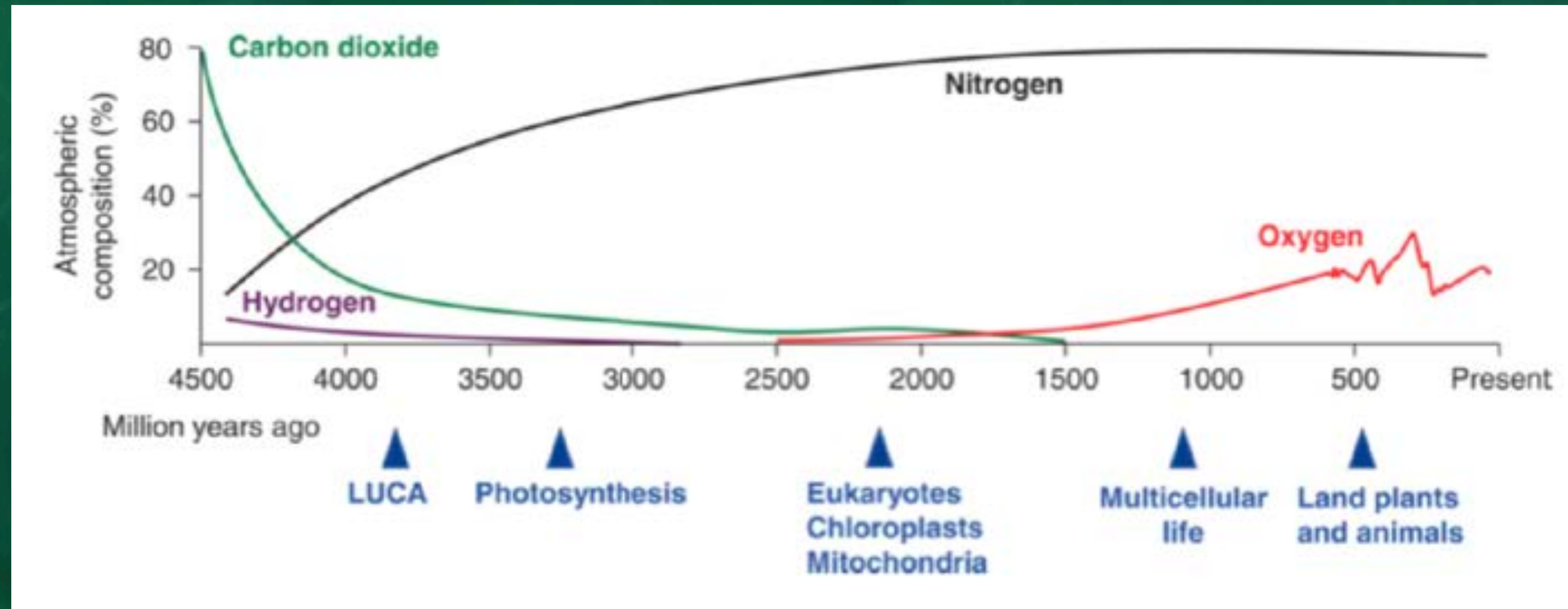


Figure 2. Coupling Quanta, Electrons, Protons, and ATP

Combined cyclic and noncyclic photophosphorylation, assuming $H^+/3ATP = 14$. Stoichiometries are depicted for four electrons transferred from H_2O to $NADP^+$ (cf. Figure 1). This gives one O_2 molecule and two NADPH molecules. Three ATP molecules will be made, provided photosystem I recycles one electron in order to contribute two protons to the proton motive force.





Stromatolite reef, showing layers formed as each surface bacterial mat trapped sediment and deposited calcium carbonate.

Alive on a silent earth, before the Rocky Mountains, the Mississippi River, the Atlantic Ocean, Everest, trees.

1,700,000,000 years before the first dinosaur egg hatched.

Catching photons from the sun and tearing water apart, breathing out oxygen into a sea without fish.

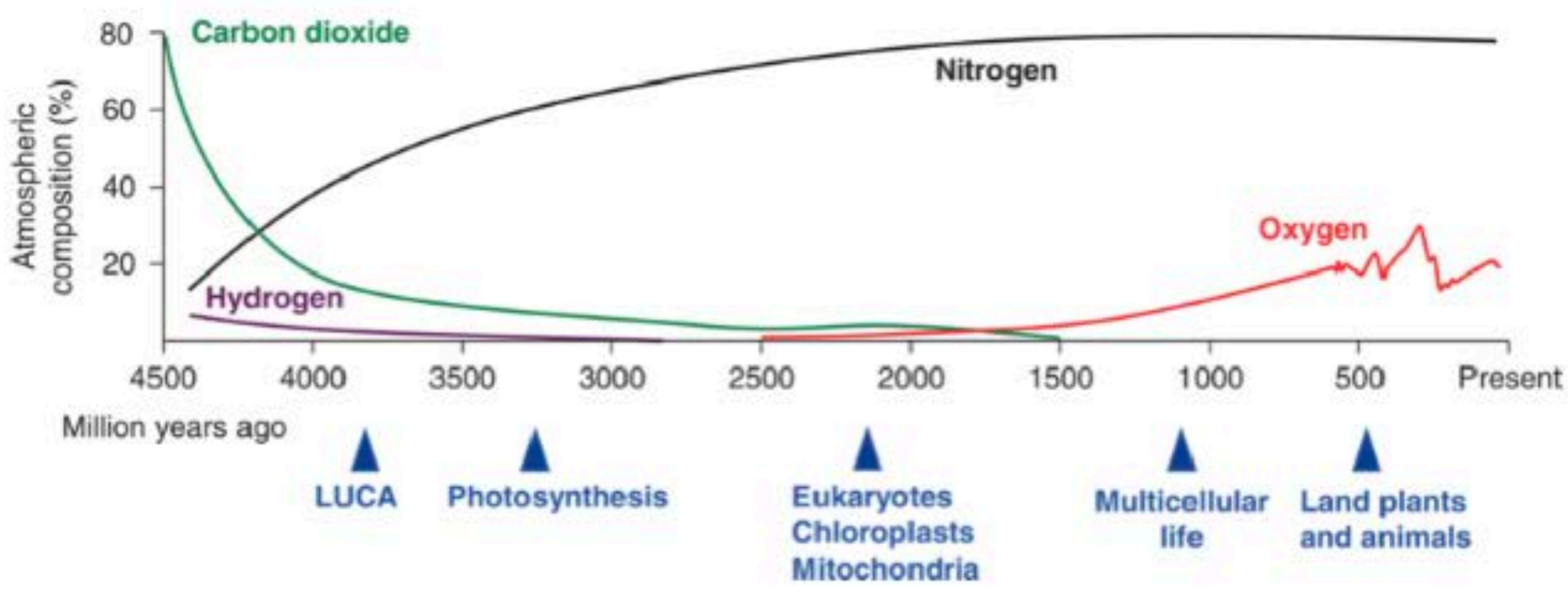
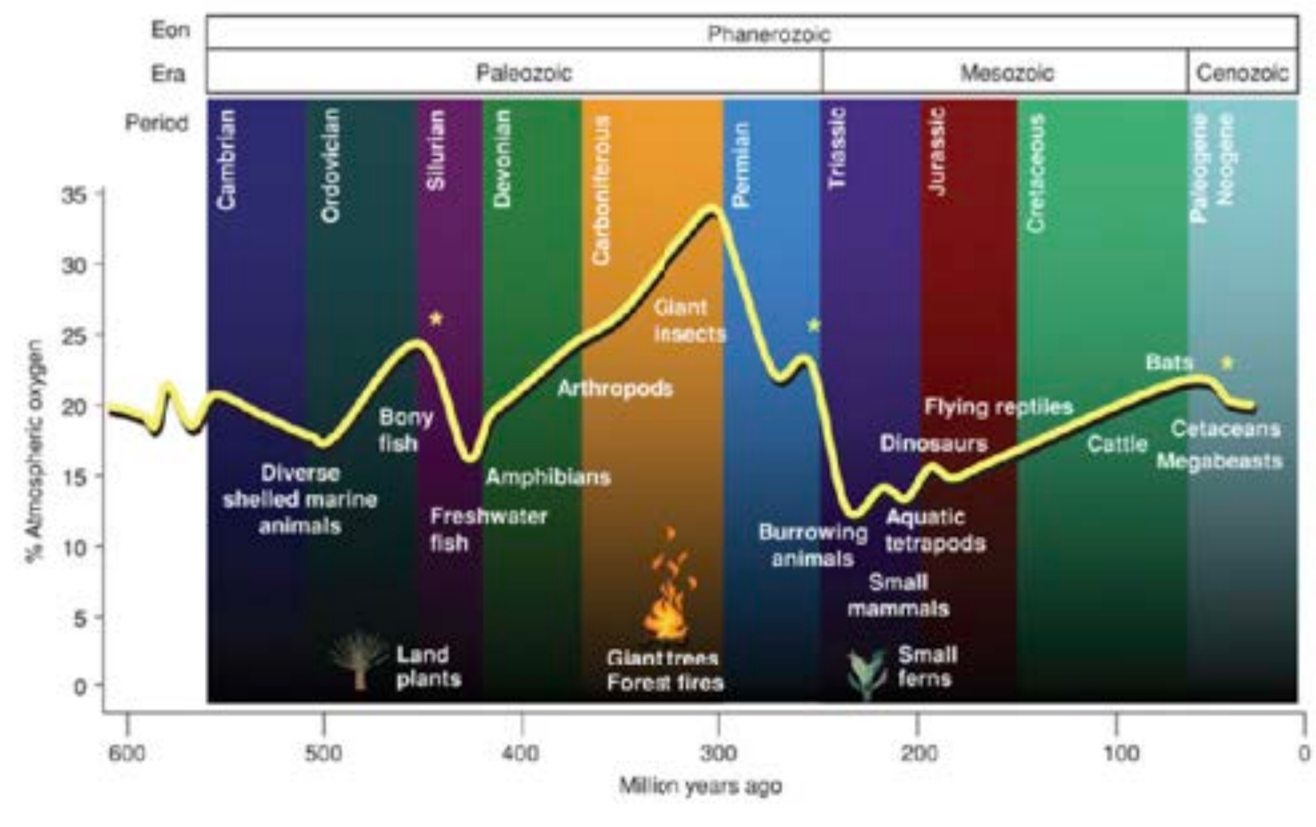


Figure 4.
A general model of early evolution and atmospheric O_2 concentration. Last Universal Common Ancestor (LUCA) was anaerobic and unicellular, but possessed heme proteins and their equivalents for antioxidation and reactive O_2 species-mediated cell signaling and possibly ATP production. Photosynthesis by cyanobacteria led to O_2 accumulation, which was initially stored in rocks and sediments but later enriched the atmosphere. Eukaryotic plant and animal cells evolved that can more efficiently produce and utilize O_2, leading to multicellular organisms of increasing complexity. Around 500 Ma, atmospheric O_2 level reached the contemporary range, coinciding with an explosive appearance of terrestrial plants and animals.



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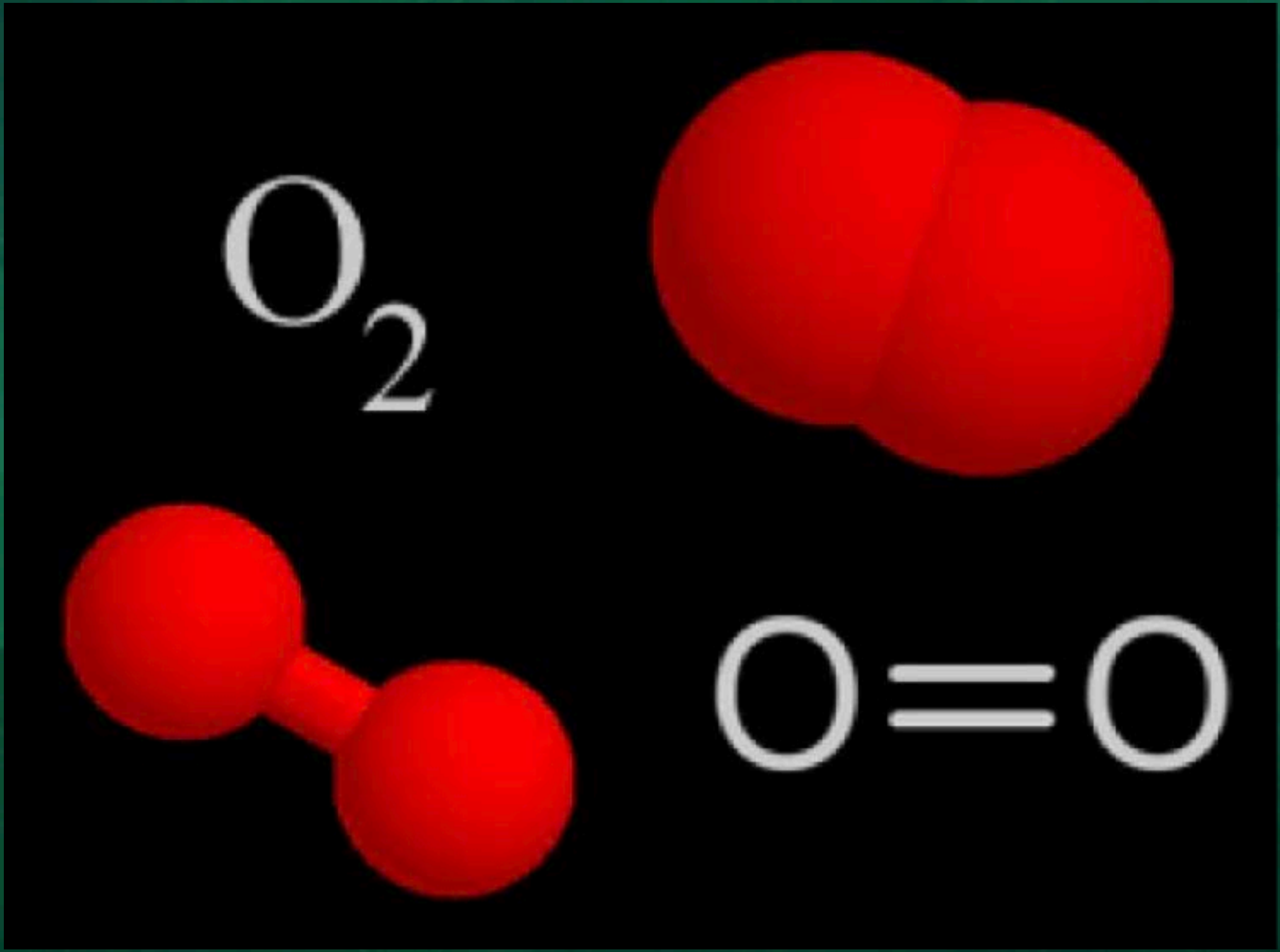
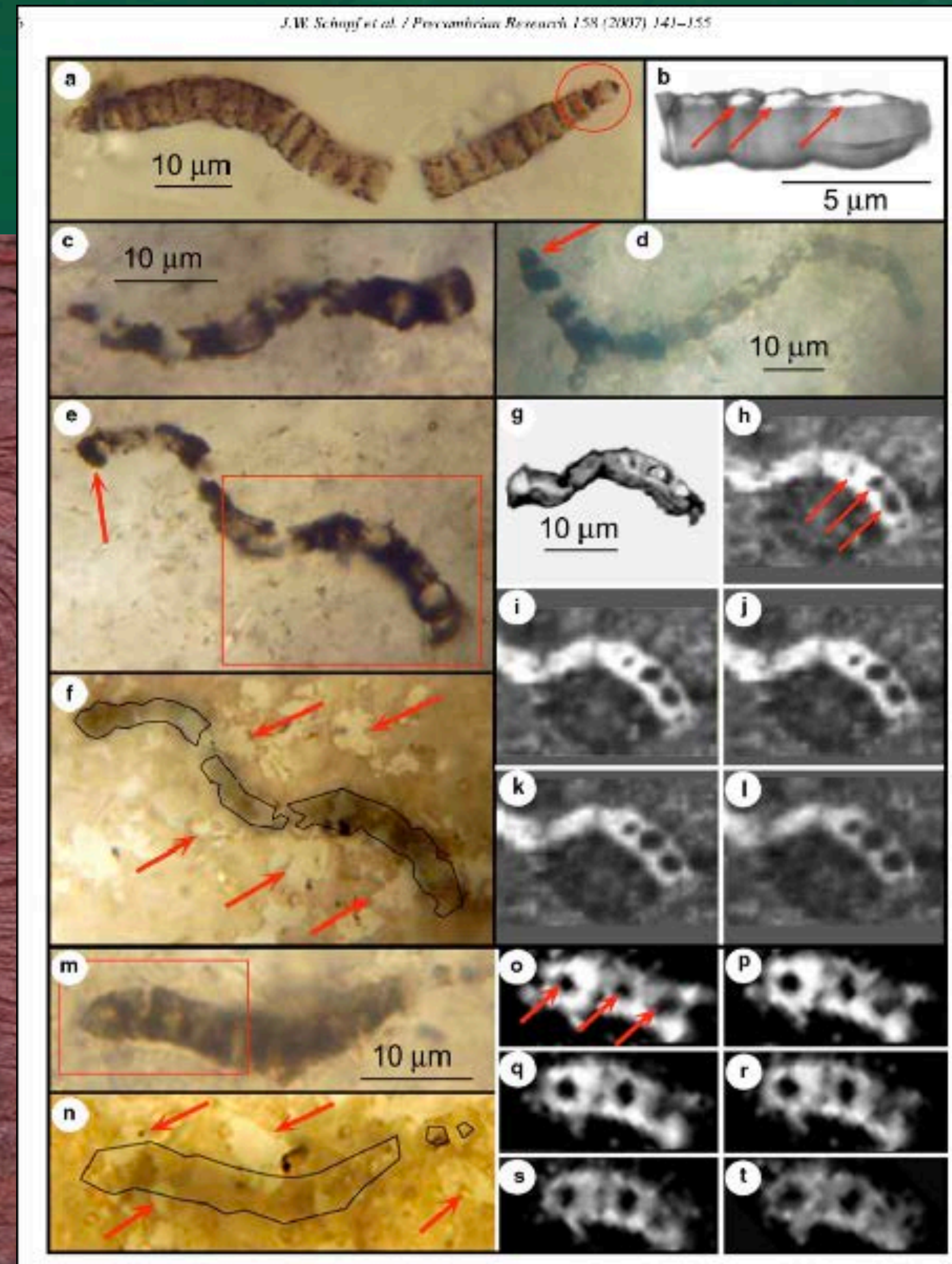

O_2
O=O

stromatolite fossil
along S. Kaibab Trail
- Grand Canyon -



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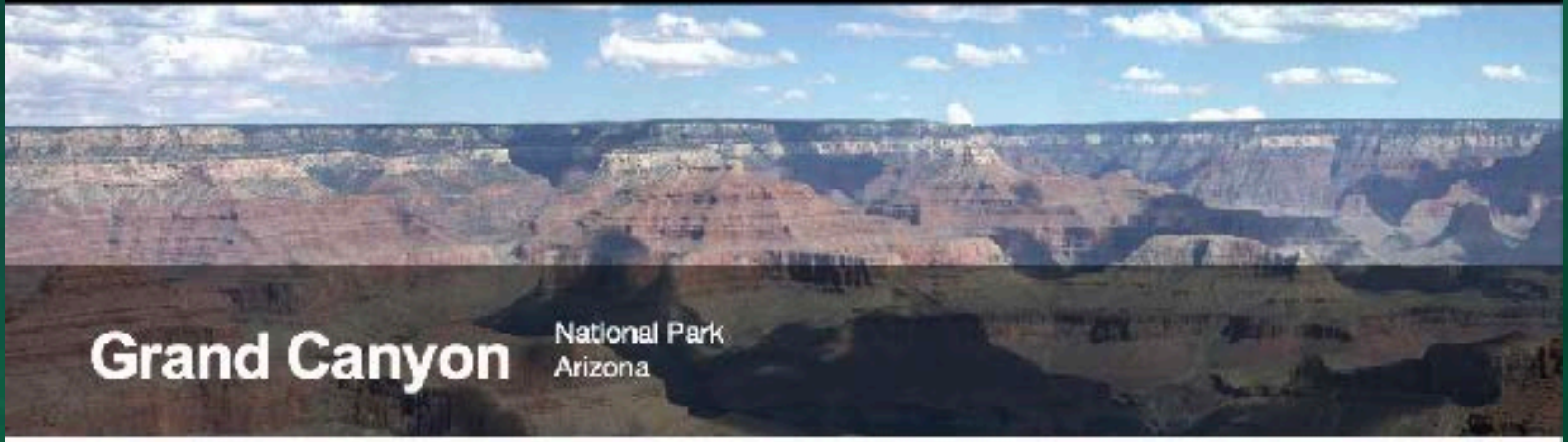
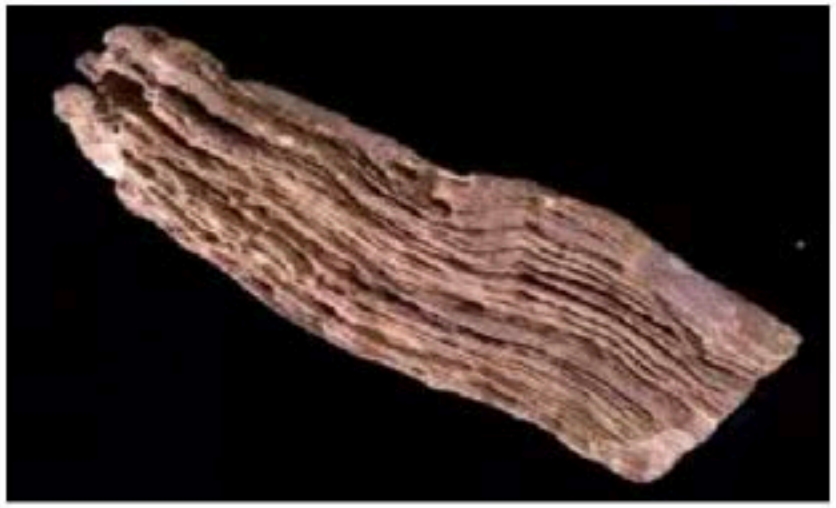
National Park Service



Marine Fossils

With marine environments creating many of the sedimentary rock layers in the canyon over the past 525 million years, marine fossils are quite common. Species changed over time, but similar fossils can be found in most of the marine-based rocks at Grand Canyon.



Stromatolites fossil.

Stromatolites

The oldest fossils at Grand Canyon are 1,200 million to 740 million years old. Stromatolites are the limestone structures formed by photosynthesizing bacteria called cyanobacteria. They created layers of alternating slimy bacteria and sediment in very shallow water, dominating shallow seas until predators, such as trilobites, came into the picture. Today stromatolites only live in a few shallow ocean areas with high salinity. The salinity deters predation and allows the stromatolites to survive.

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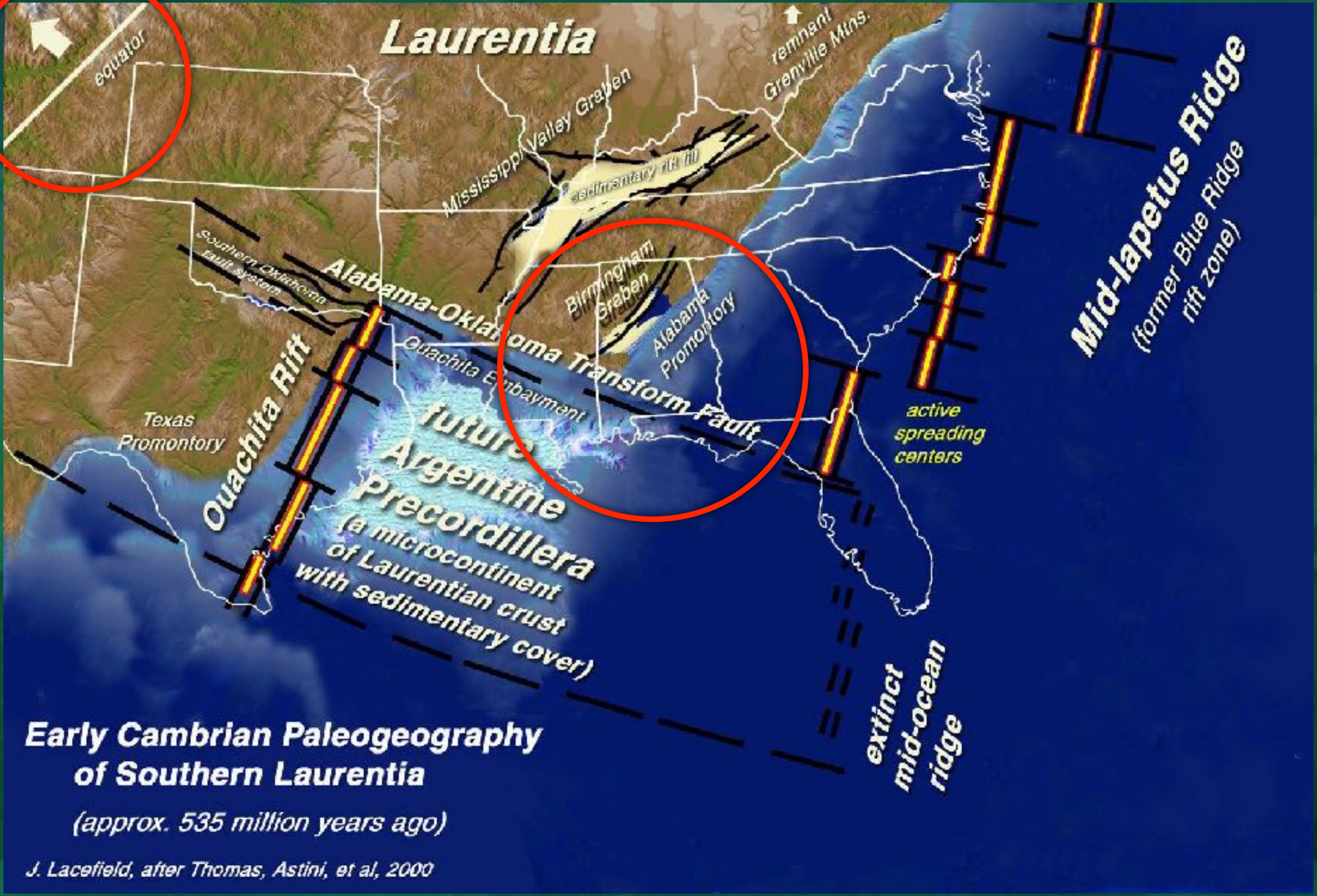
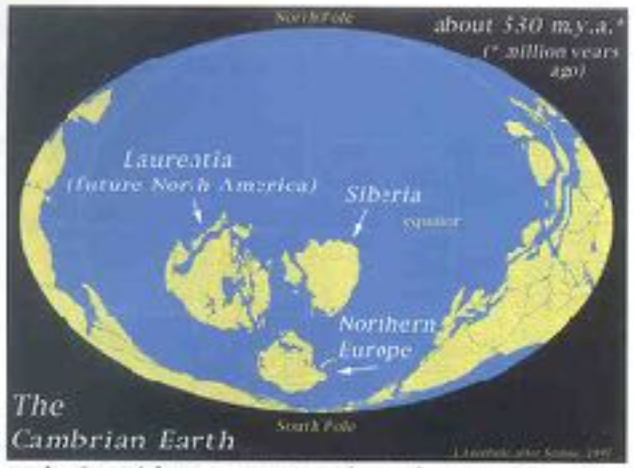

Laurentia
equator
remnant Grenville Mtns.
Mississippi Valley Graben
sedimentary rift fill
Southern Oklahoma fault system
Alabama-Oklahoma Transform Fault
Birmingham Graben
Alabama Promontory
Ouachita Embayment
Ouachita Rift
Texas Promontory
future Argentine Precordillera
(a microcontinent of Laurentian crust with sedimentary cover)
active spreading centers
Mid-Iapetus Ridge
(former Blue Ridge rift zone)
extinct mid-ocean ridge
Early Cambrian Paleogeography of Southern Laurentia
(approx. 535 million years ago)
J. Lacefield, after Thomas, Astini, et al, 2000



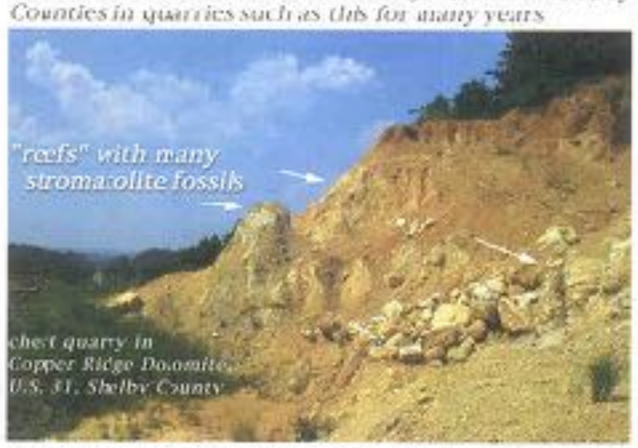
geologic evidence suggests that what was then the southern part of Alabama and several adjoining states may have rifted away from the rest of North America during the supposedly calm early part of the Cambrian Period and drifted across the expanding ocean basin, eventually to become part of what is now Argentina.

During the latter half of the Cambrian, sea levels continued to rise and cover much of the North American continent, depositing marine rocks over a wide area that today is exposed as dry land. This sea level rise, or **transgression**, was not a smooth event, and included many episodes of **regression**, or falls in sea level, occurring within the general pattern of rise. The flatness of the Cambrian landscape allowed shallow ocean waters to move easily back and forth across a large part of the continent.

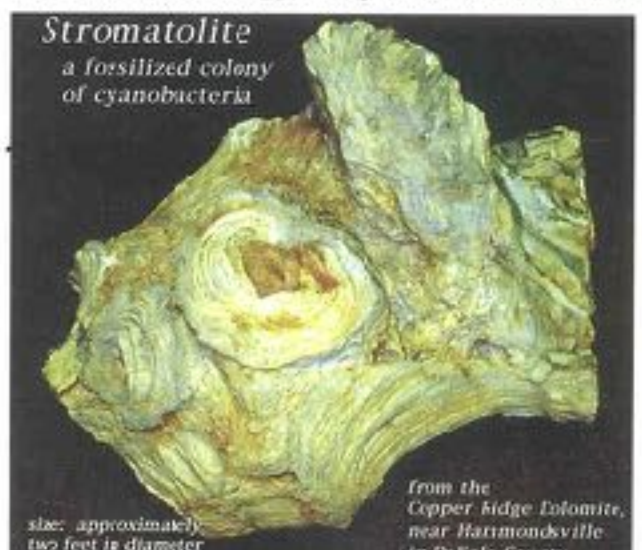
The oldest of the Cambrian-aged rocks in Alabama is a set of sandstones and shales geologists call the **Chilhowee Group** that were deposited at or near the ocean's edge as the sea began its initial transgressive rise. Above these clastic rocks is a series of limestones and dolostones that were deposited on the shallow marine shelf. The oldest of these carbonate rocks is called the **Shady Dolomite**. Above the Shady are found the **Rome** (Early Cambrian) and **Conasauga** (Middle Cambrian) **Formations** and lower **Knox Group**, that includes the Copper Ridge Dolomite. Several of these carbonate-based rocks have been replaced by silica to form chert. A few contain thick bands of evaporation minerals, suggesting that this shallow sea had restricted circulation and even dried up in places under the hot, tropical sun.

Rocks from the Cambrian Period crop out over a fairly limited area of the state, mostly in the Valley and Ridge Province. These outcrops are places where the folds of the Appalachians have moved these once deeply buried rocks to the earth's surface, especially in spots where erosion has removed the overlying younger strata. The **Copper Ridge Dolomite**, which is Late Cambrian in age, is one of the major ridge-forming rock units in the Alabama Valley and Ridge province.

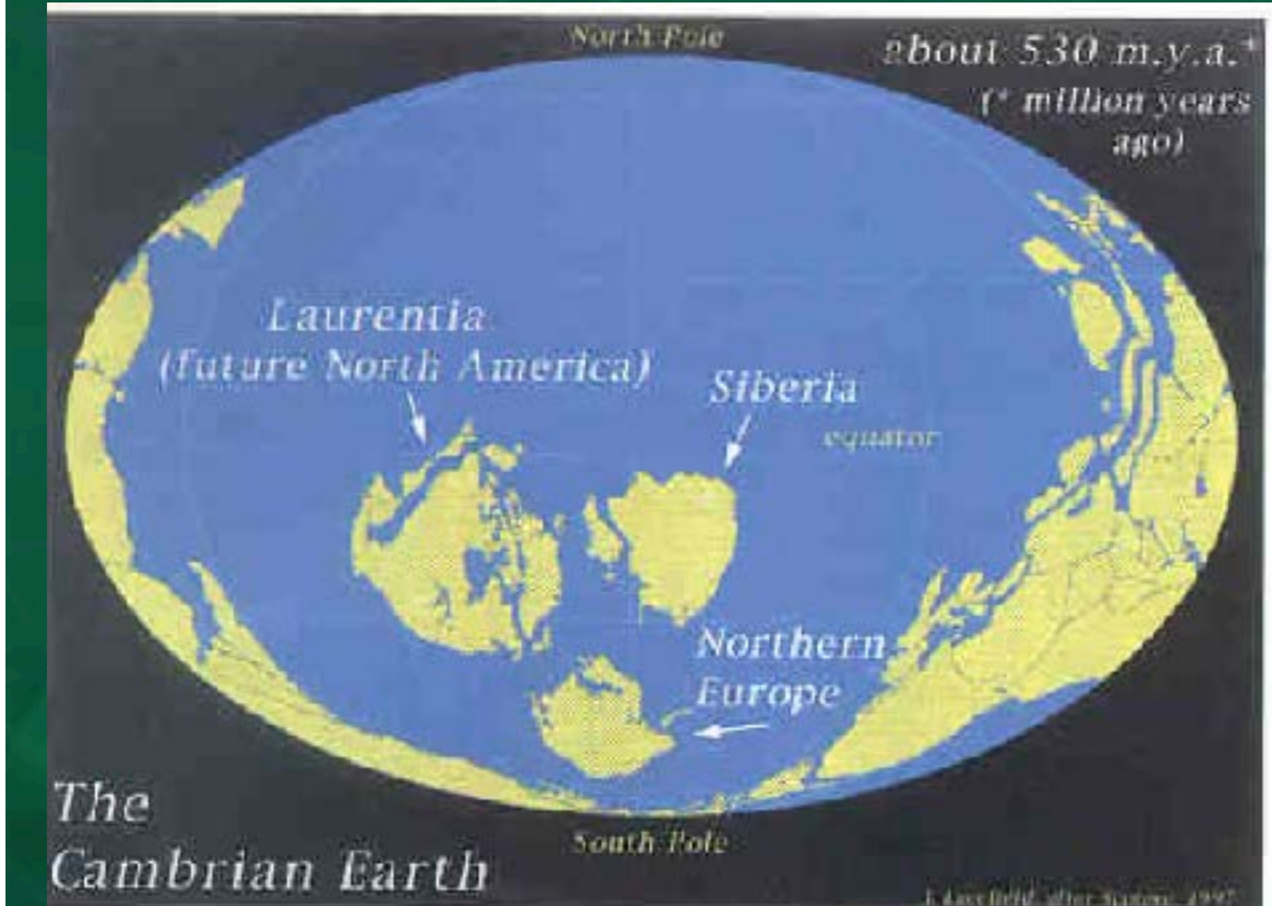
Cambrian-aged limestones and dolostones exposed in a quarry near Helena. The Conasauga Formation and the Ketona Dolomite have been mined in Jefferson and Shelby Counties in quarries such as this for many years.

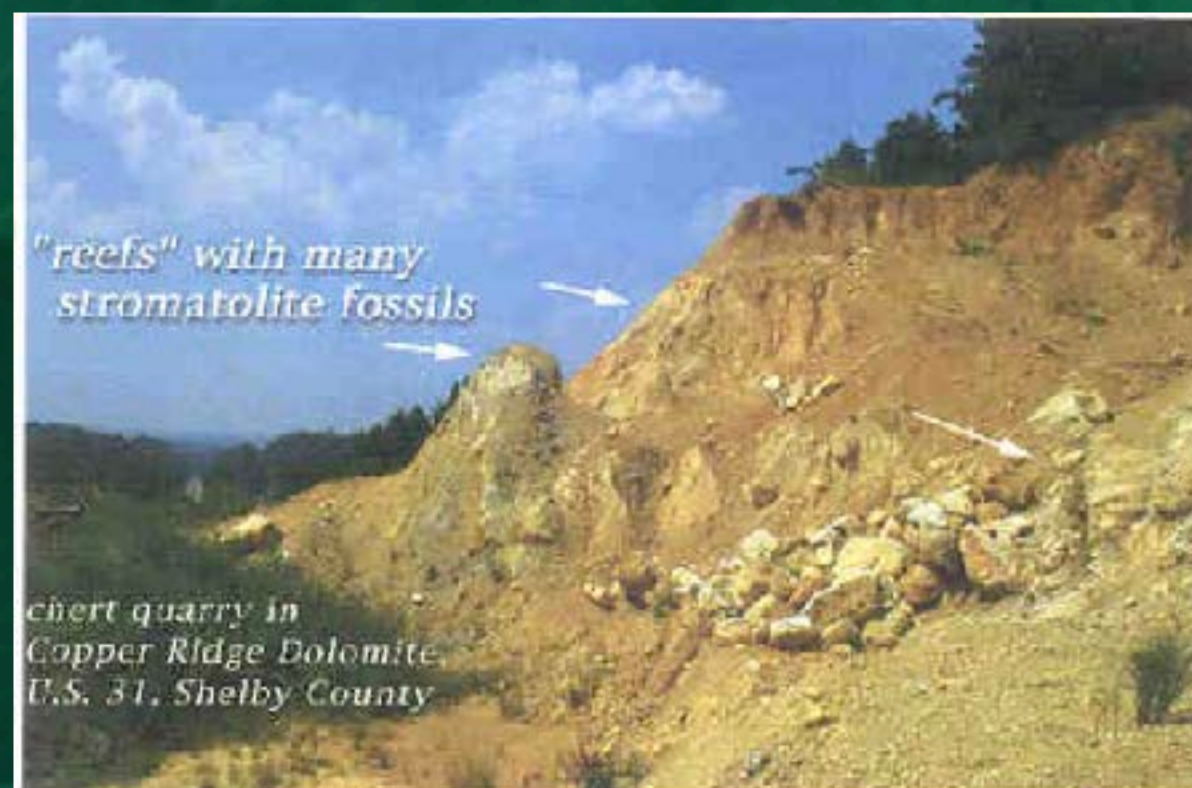


Chert quarry of the Copper Ridge Dolomite near Pelham.

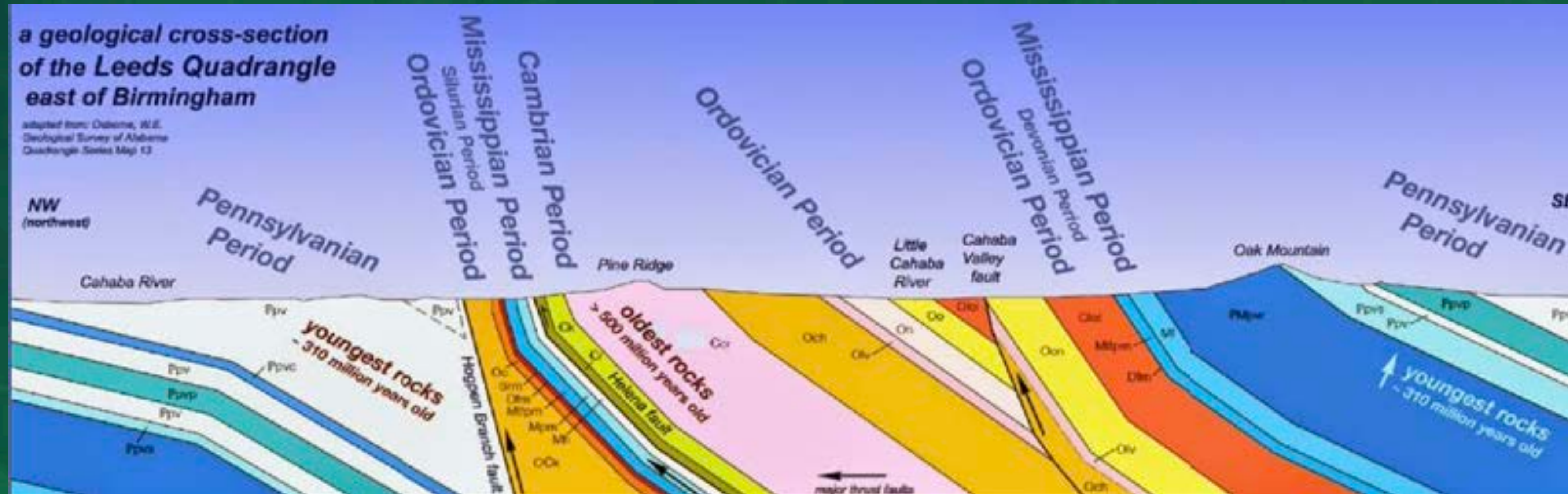


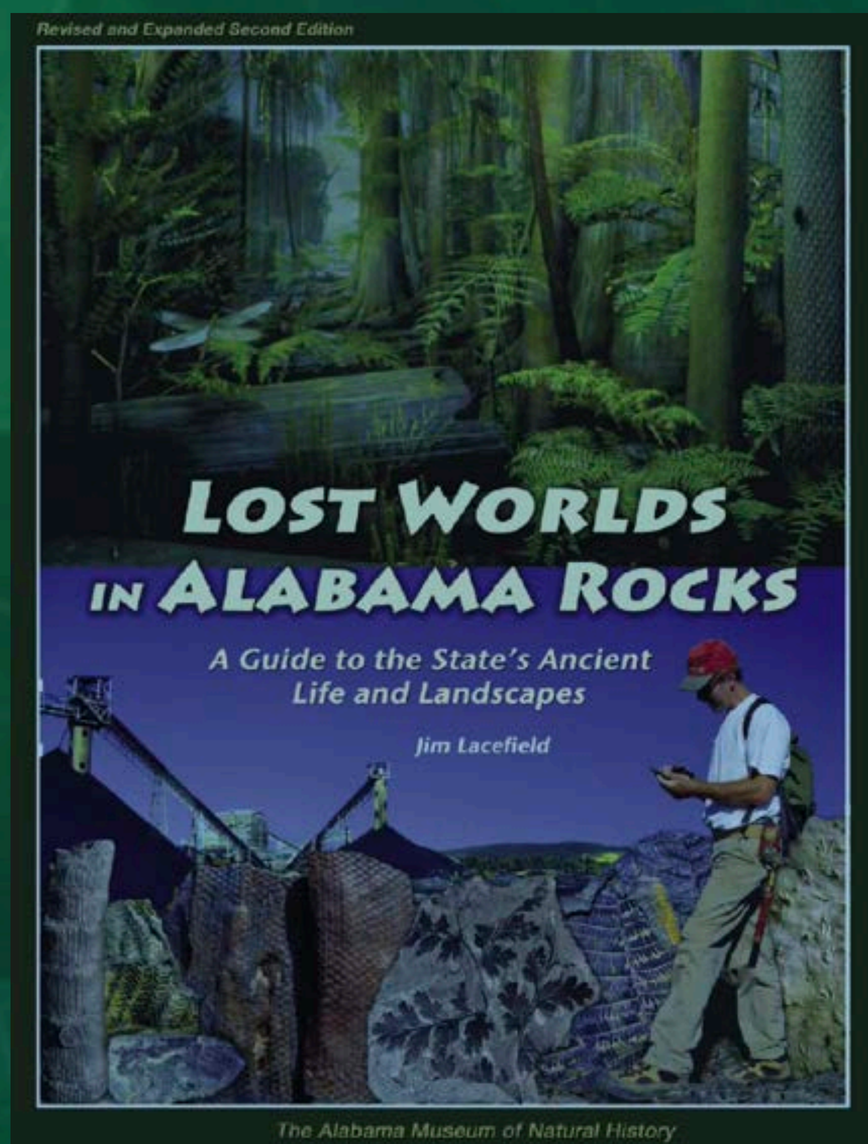
Stromatolite fossils in chert have incorrectly been called "fossil hornets' nests" because of their appearance.





Chert quarry of the Copper Ridge Dolomite near Pelham.





Geological evidence shows the sea has risen to cover the land of Alabama many times during the past. The state's present-day landscape is literally built on the remains of ancient sea floors.

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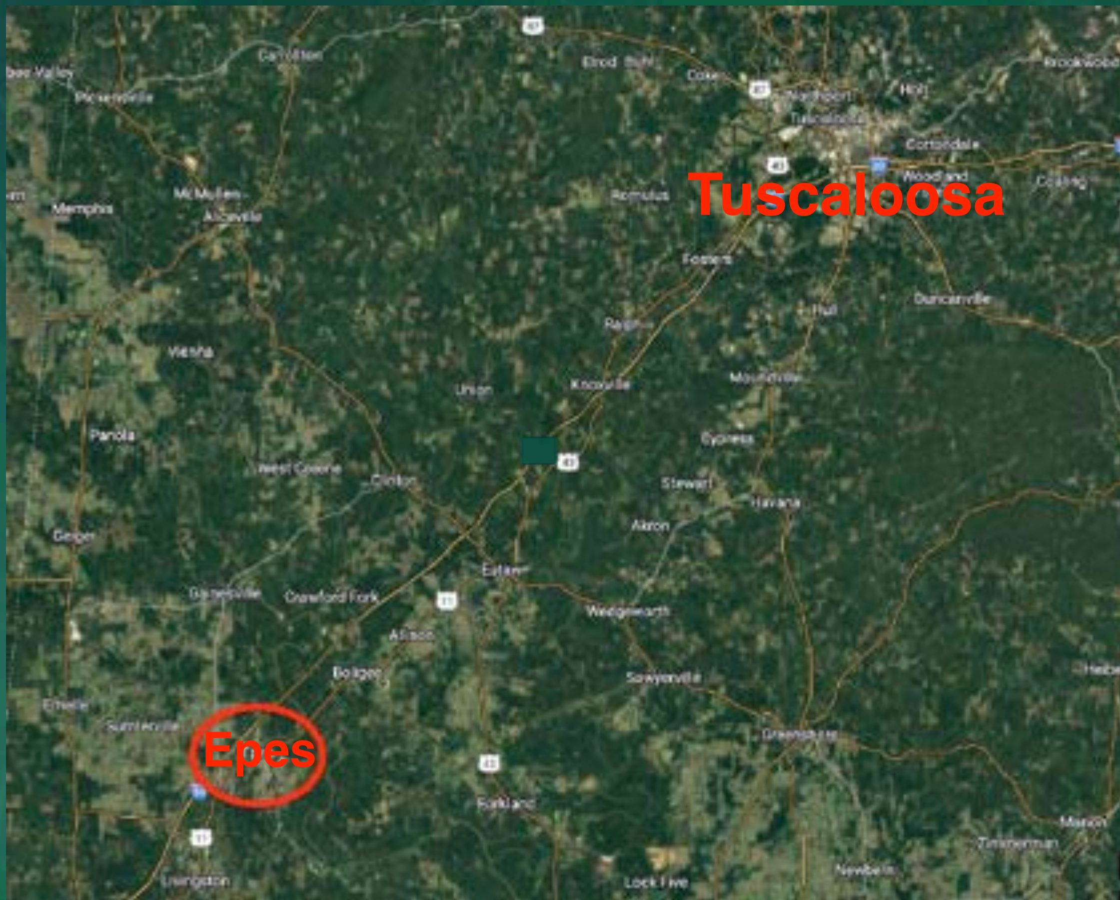
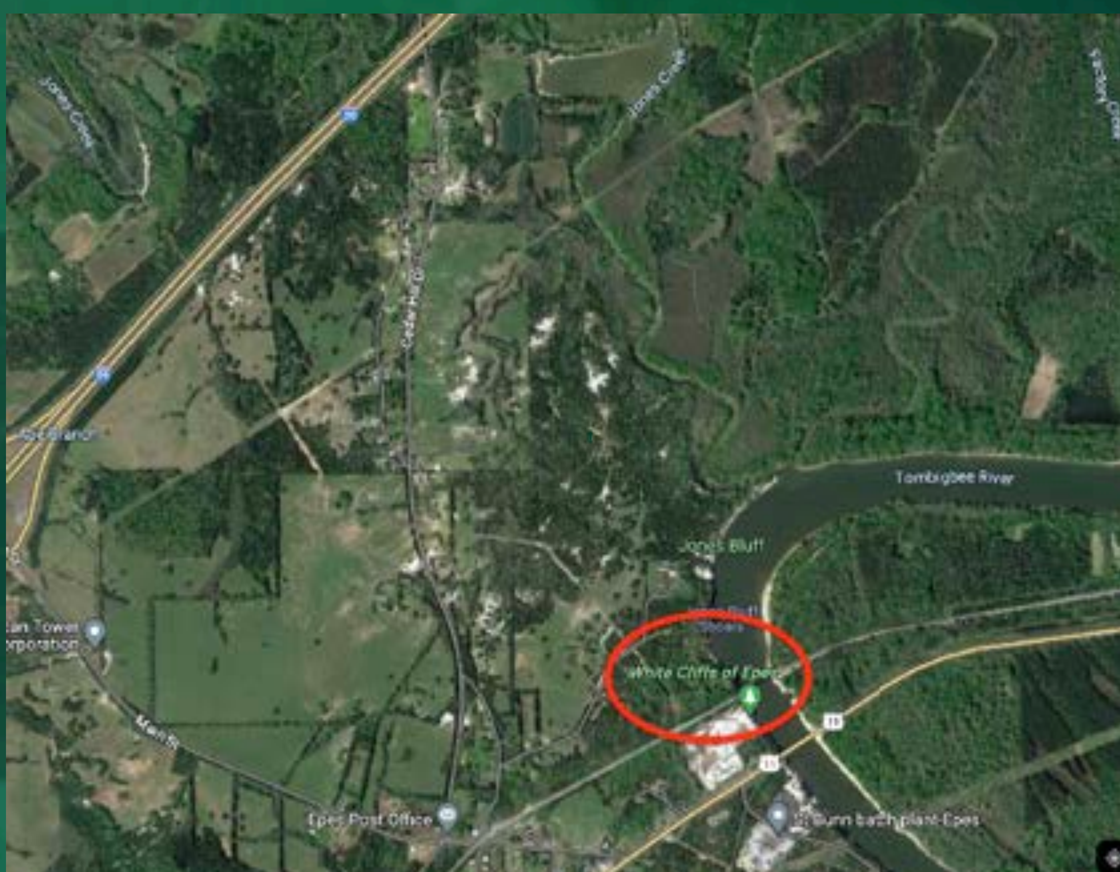
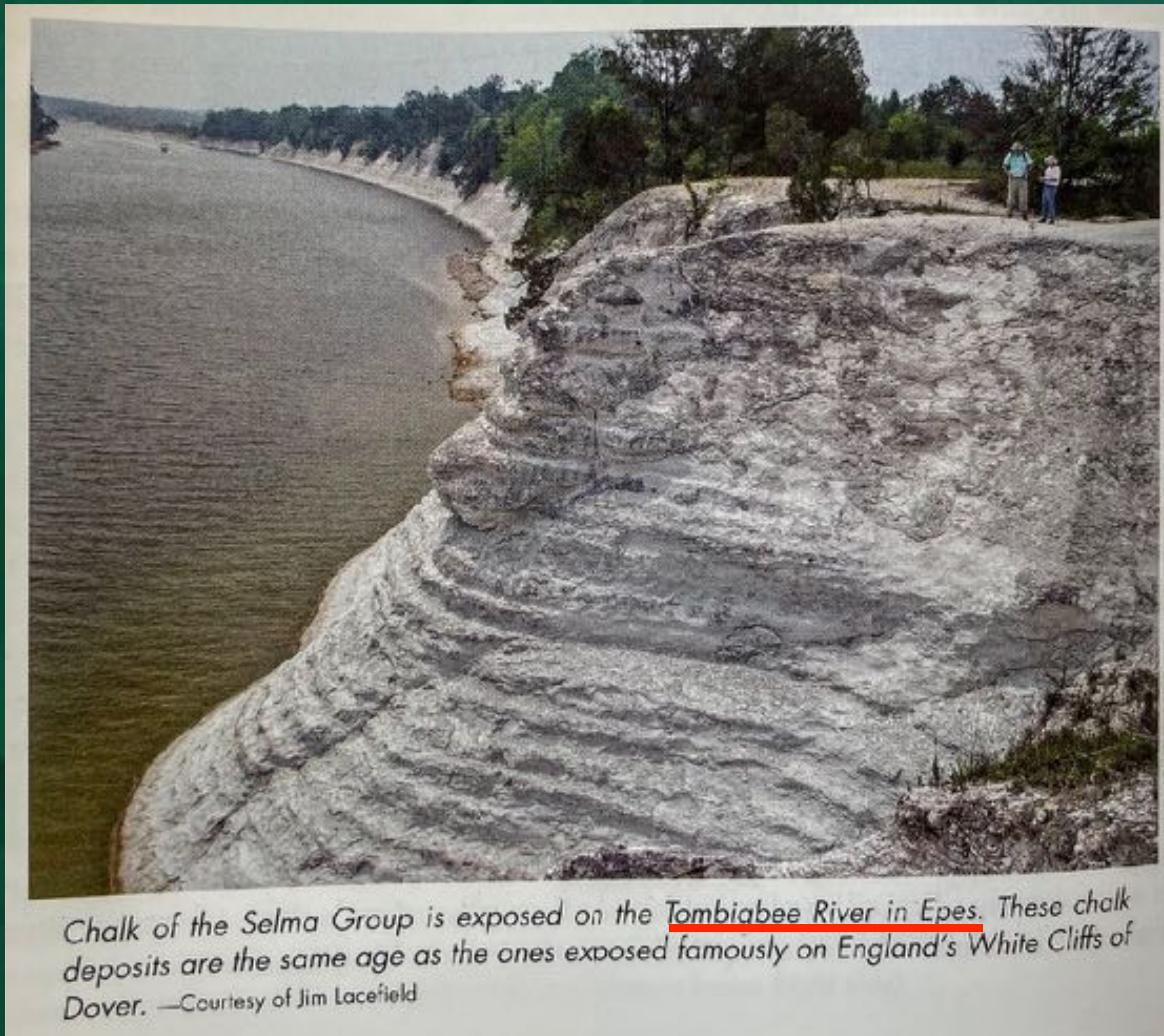





Chalk of the Selma Group is exposed on the Tombigbee River in Epes. These chalk deposits are the same age as the ones exposed famously on England's White Cliffs of Dover. —Courtesy of Jim Lacefield

White Cliffs of Epes (!)

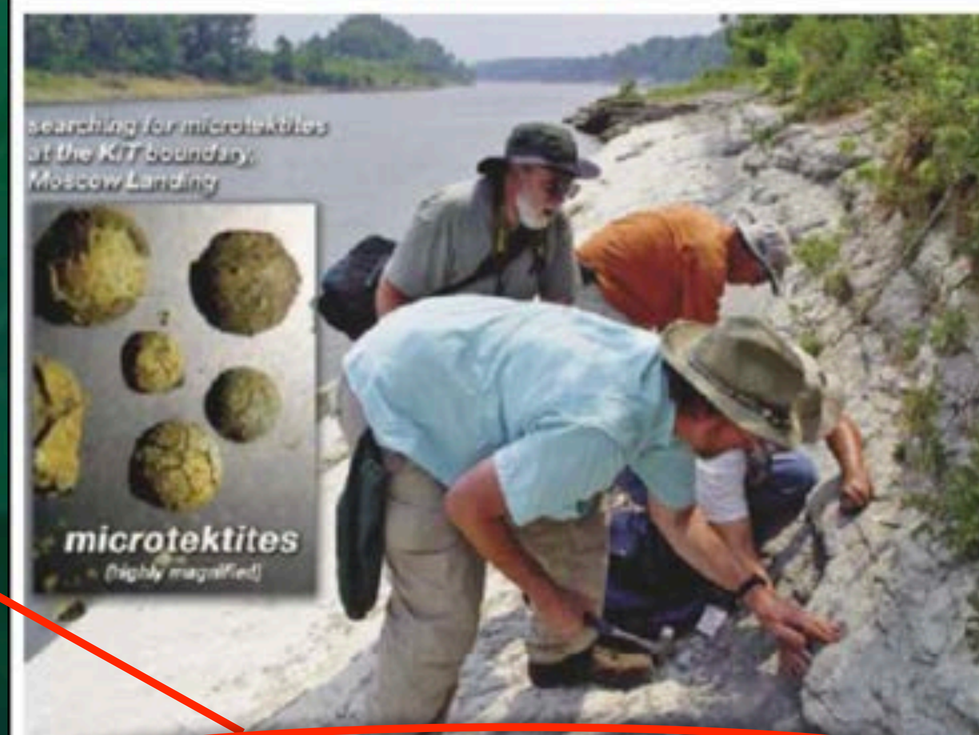
A Timetable of Alabama Geologic History

Era	Time Period	Epoch	When Began (in millions of years)	Significant Events in Alabama's Geologic History
Cenozoic Era	Quaternary	Holocene	10,000 years	our present epoch of Earth history
Cenozoic Era	Quaternary	Pleistocene	2.6	the "Ice Age"; Alabama ecosystems unlike today—northern tree species, megafauna
Cenozoic Era	Tertiary Period	Pliocene	5	Alabama landscape undergoes slight uplift, deep erosion of uplands
Cenozoic Era	Tertiary Period	Miocene	23	Earth's climate becomes unstable; fossil pollen studies show deciduous trees start to dominate Alabama forests
Cenozoic Era	Tertiary Period	Oligocene	34	
Cenozoic Era	Tertiary Period	Eocene	56	Alabama climate warm and wet, forests still contain many tropical tree species: lignite coal forms in Gulf coastal marshes
Cenozoic Era	Tertiary Period	Paleocene	65	
Mesozoic Era	Cretaceous		146	sea levels very high, warm oceans cover most of Alabama; "Selma chalk" forms offshore; dinosaurs roam tropical jungles
Mesozoic Era	Jurassic		200	opening of the Gulf of Mexico; Alabama climate still hot and dry; rich oil deposits form along edge of young, expanding Gulf
Mesozoic Era	Triassic		251	supercontinent of Pangaea begins to rift apart; Alabama moves north of the equator; state's climate and landscape desert-like
Paleozoic Era	Permian		299	probable peak of Appalachian Mtn. formation, Alabama locked within dry interior of Pangaea, no rocks from this time known from the state
Paleozoic Era	Carboniferous	Pennsylvanian	318	"Coal Age" forests; Pangaea forms
Paleozoic Era	Carboniferous	Mississippian	359	widespread limestones deposited
Paleozoic Era	Devonian		416	sometimes called the "age of fishes", but land plants and animals also diversify and move further from the water's edge
Paleozoic Era	Silurian		444	Birmingham's Red Mountain iron ores form; terrestrial (land) environments first invaded by plants and animals
Paleozoic Era	Ordovician		488	tropical seas cover most of the state; Alabama rocks show mountain-building, volcanic activity was nearby to the east
Paleozoic Era	Cambrian Period		542 million years ago	Alabama on passive margin of ancient North American continent Laurentia; earliest fossils appear in Alabama rocks
"Precambrian"	"Precambrian" (represents about 87% of the Earth's history)			first multicellular organisms appear in the fossil record Grenville mountain-building episode; deep crust beneath Alabama added
"Precambrian"	Proterozoic Eon		2.5 billion	first "free" oxygen accumulates in the Earth's atmosphere
"Precambrian"	Archaean Eon		3.8 billion	earliest fossilized bacteria appear in the geologic record
"Precambrian"	Archaean Eon		4 billion	age of Earth's oldest known rocks

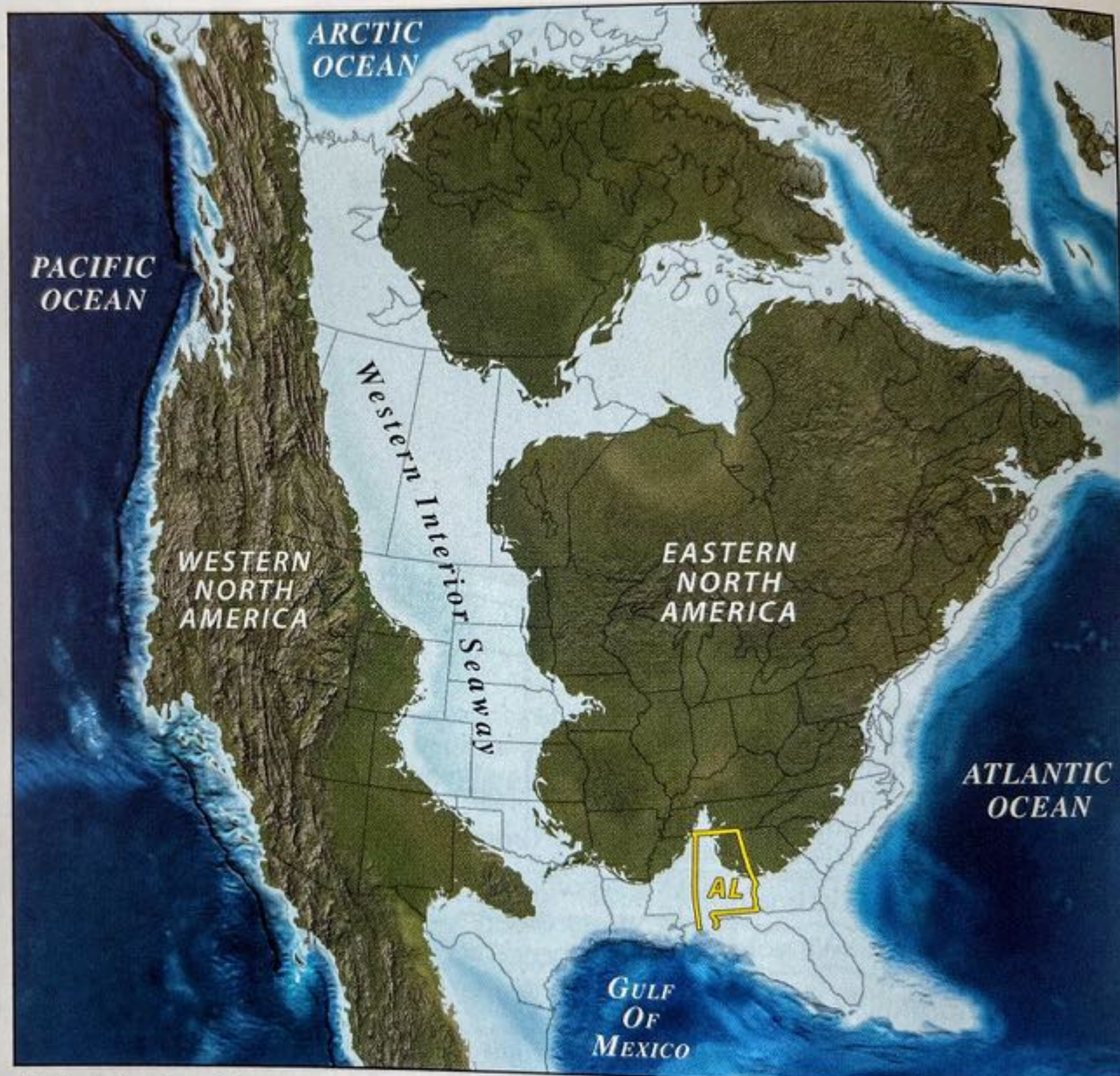
Life and the Land Through Time

The Shell Creek site is the easternmost impact ejecta bed tied to the Chicxulub impact discovered so far.

A third Alabama K-T boundary site has recently been identified at Mussel Creek in Butler County. Further study of the sediments along this important geological boundary in Alabama's Coastal Plain counties may provide further evidence about the nature of the catastrophic events that ended the world of the dinosaurs and ushed in the new age of life on Earth—the Cenozoic Era.

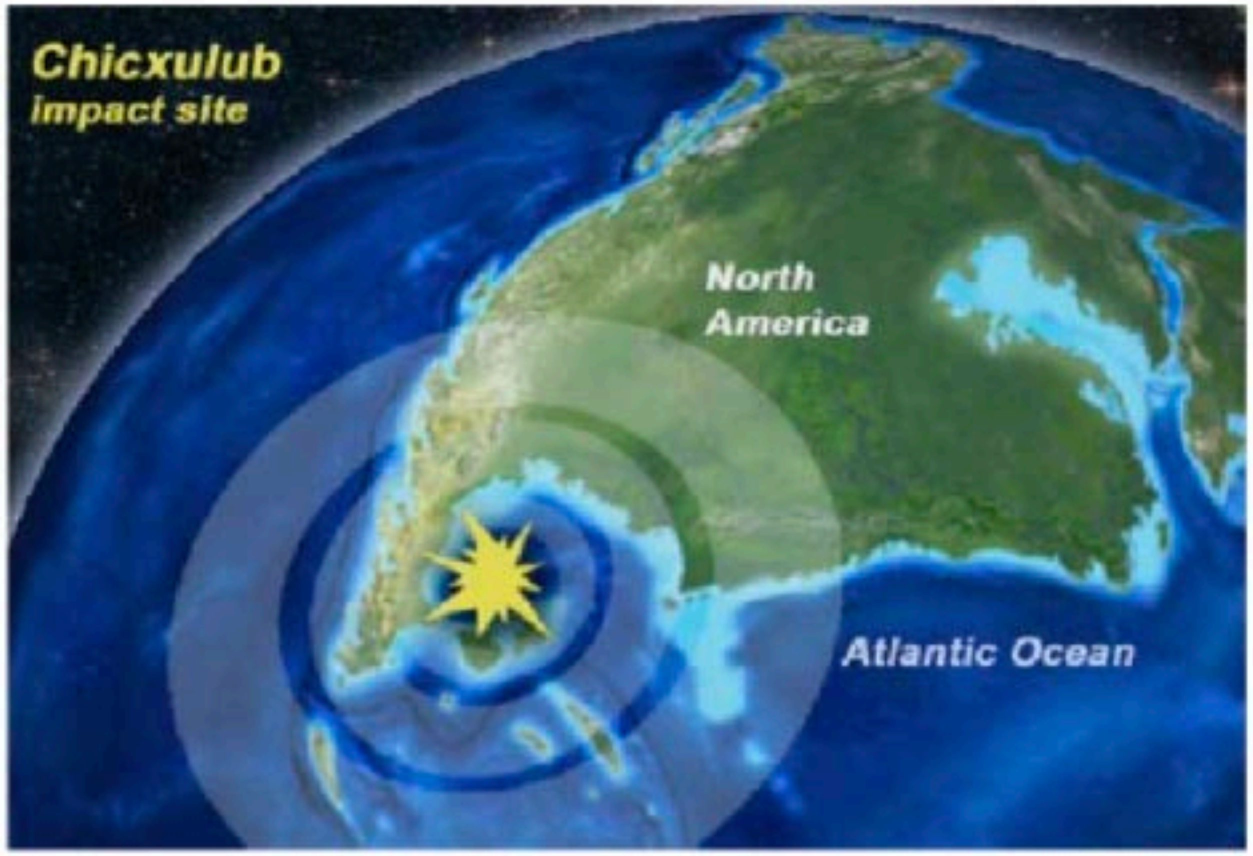


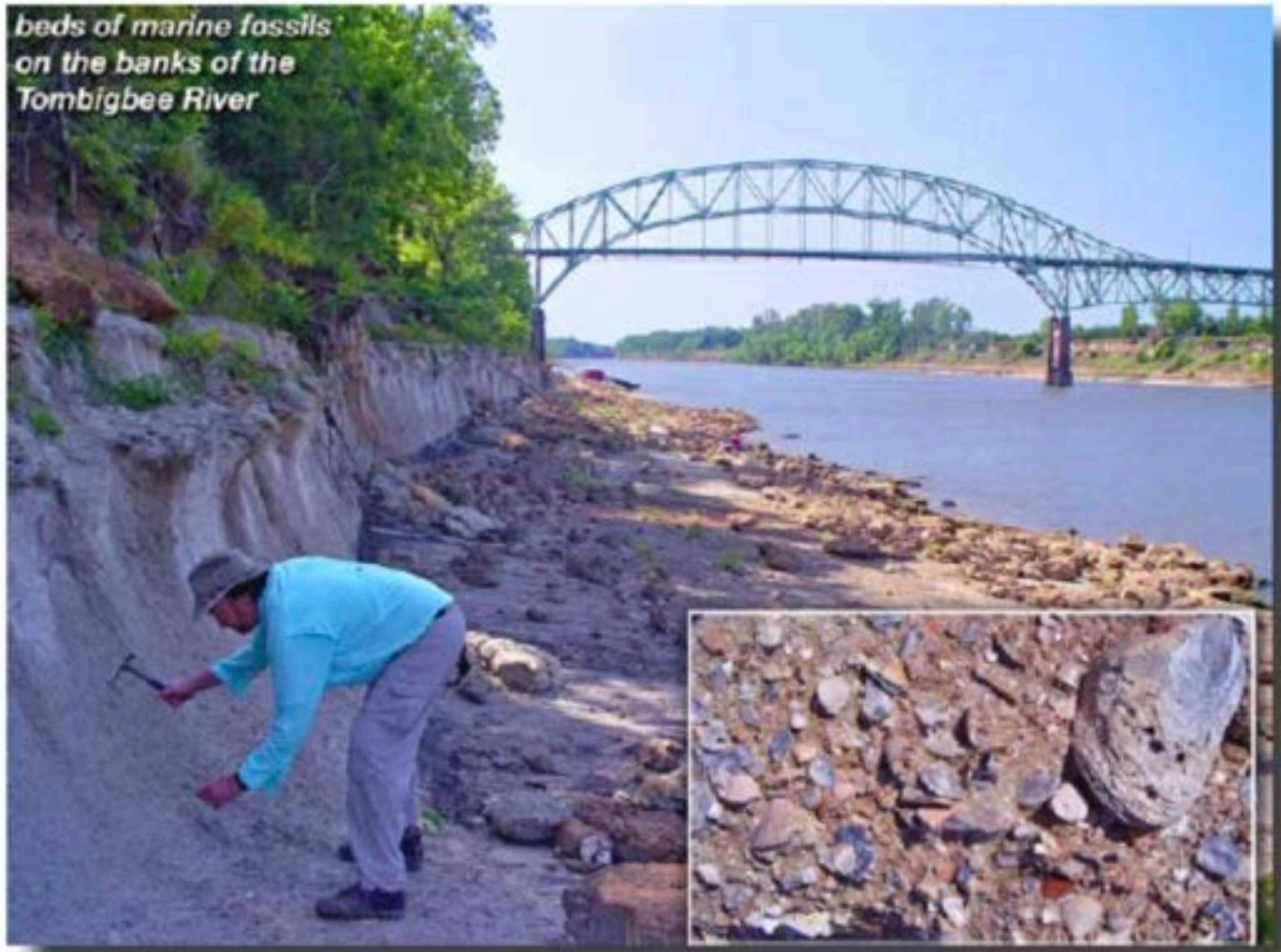
The search continues at several Alabama Cretaceous/Tertiary boundary sites for tiny, glassy beads known as ***microtektites****. Most of these small, spherical masses of impact-vaporized crust have now weathered into rounded pellets of dull clay.*



During the Late Cretaceous, sea level was at one of its highest recorded stands. Alabama lay at the southern end of an immense continental seaway that connected the Arctic Ocean and the Gulf of Mexico. —Modified from Lacefield, 2018

The geological evidence pointing to an impact includes a crater approximately 124 miles in diameter, now buried under more than 3,000 feet of limestone deposited since the time of the cataclysm. The impact created huge **tsunami**, or seismic sea waves hundreds of feet high along the Gulf of Mexico coastline which devastated the Coastal Plain for many miles inland. "Storm" deposits of unprecedented proportions dating to the time of this event are found in Texas and other areas. Tiny beads of glassy rock known as





The New World of the Cenozoic Era
(65 m.y.a. to Today)

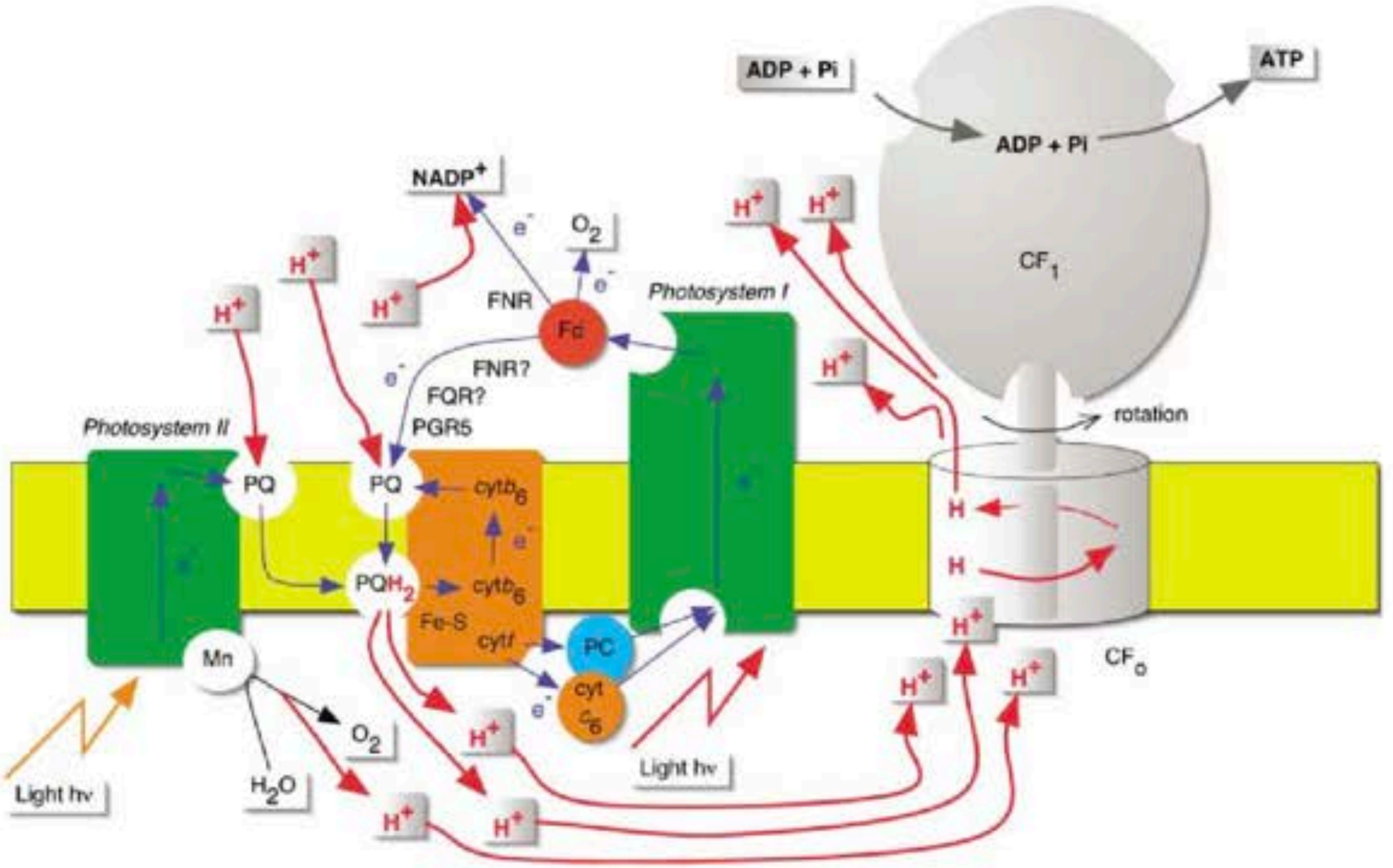
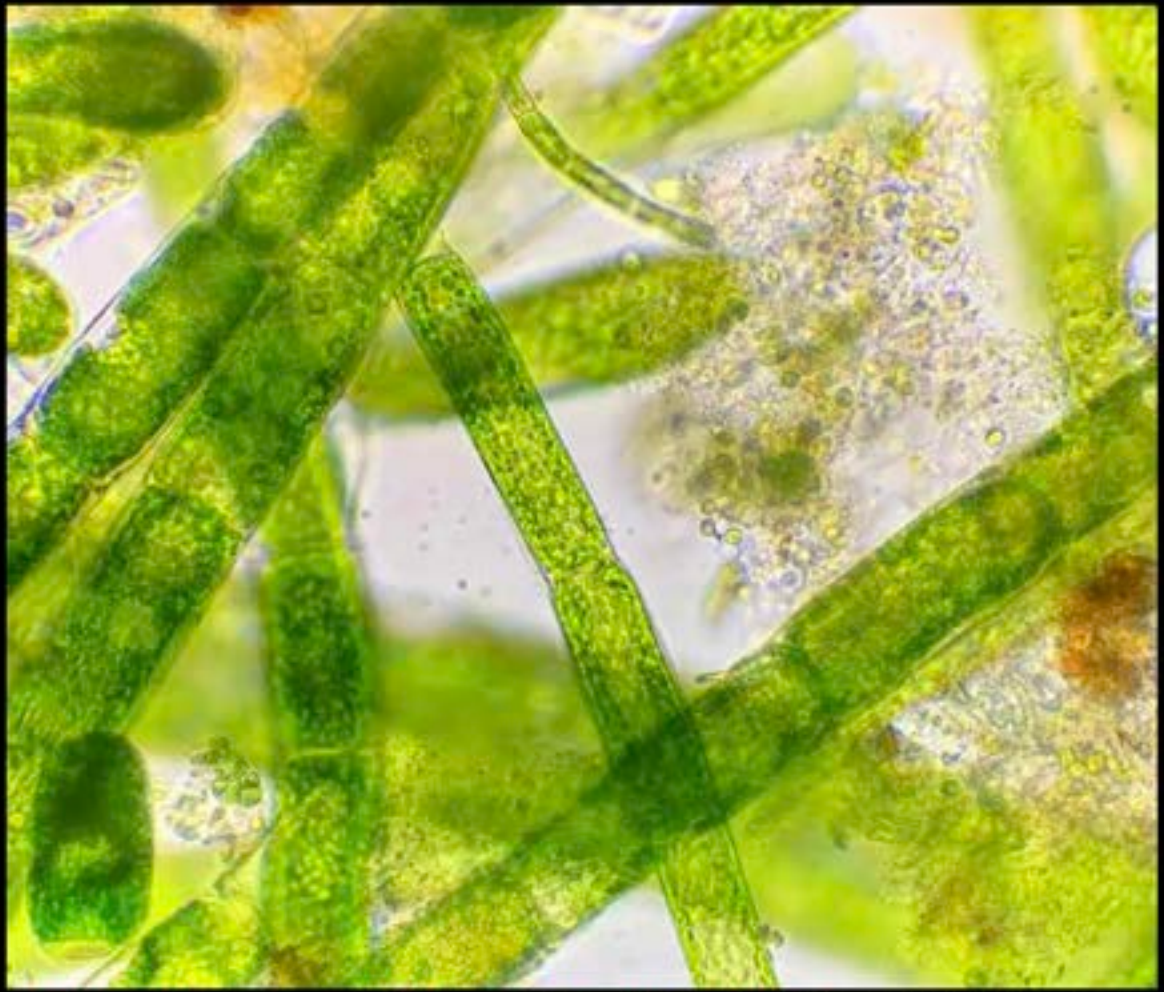
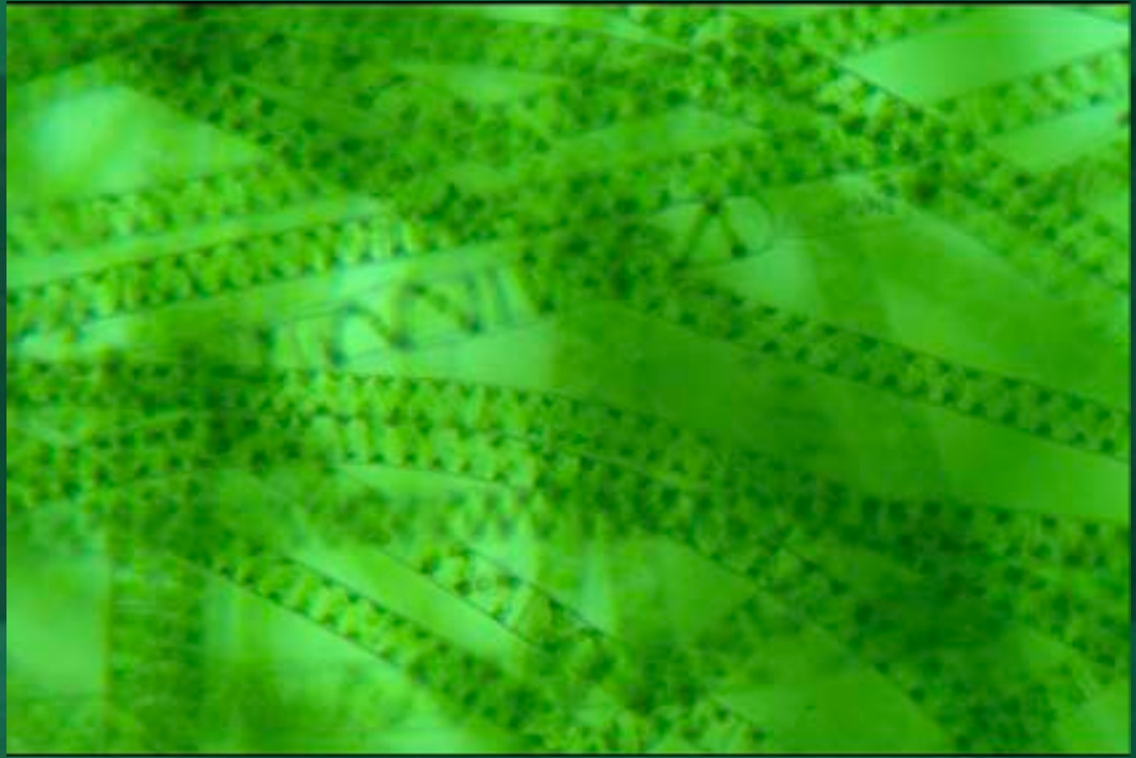


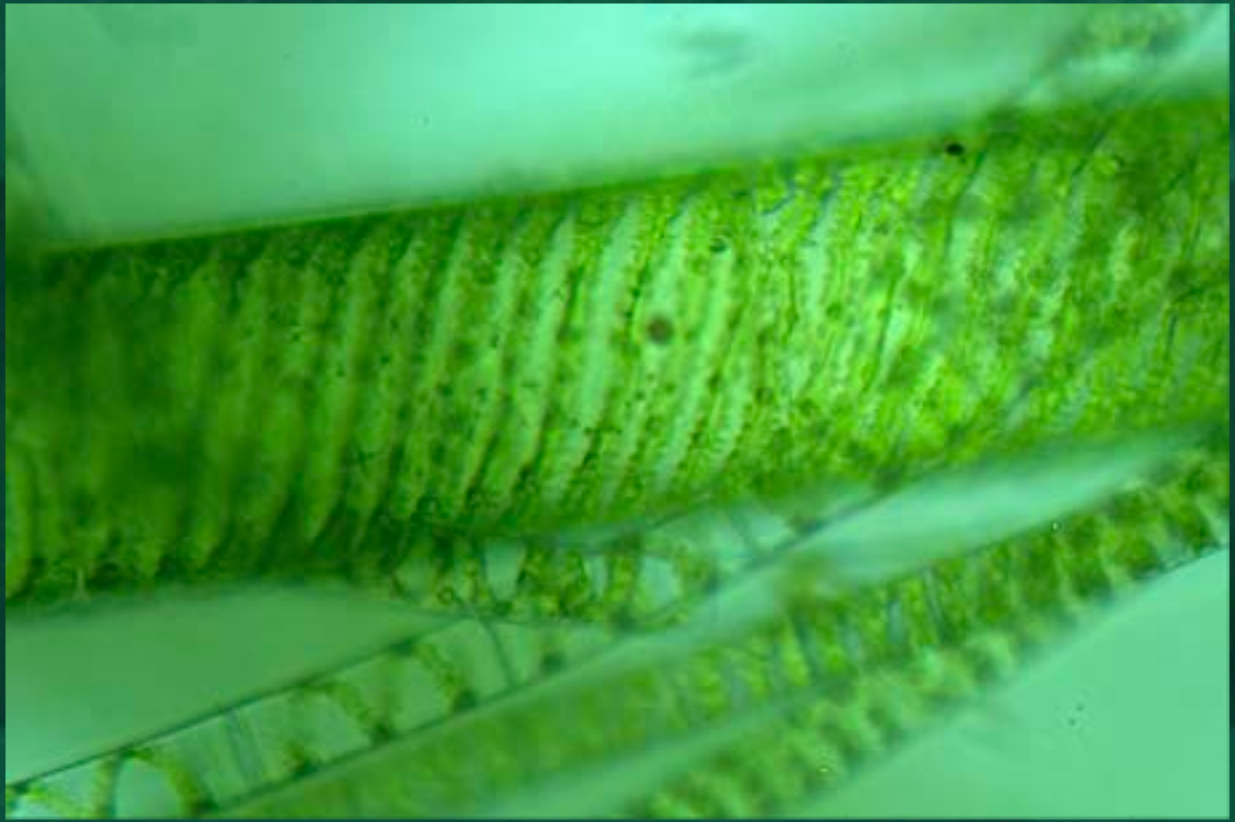
Figure 1. Photosynthesis–From Light to ATP

Electron transport (e^-) (blue) is arranged vectorially in the chloroplast thylakoid membrane (yellow). Proton (H^+) (red) translocation from the chloroplasts stroma (above the membrane) into the lumen (below the membrane) establishes a proton motive force that couples electron transport to ATP synthesis. The implied stoichiometry $3H^+/e^-$ is for noncyclic electron transport alone (cf. Figure 2). FQR is a hypothetical ferredoxin-quinone-oxidoreductase. Other abbreviations as in text. Junge's animations *Rotary ATP Synthase* and *From Light to ATP* are recommended viewing: http://www.biologie.uni-osnabrueck.de/Biophysik/Junge/overheads.html



Oedogonium and zoospores ... collected from backyard fountain pond 12/13/21: microphotographs and videos by Whitsett Boogaerts





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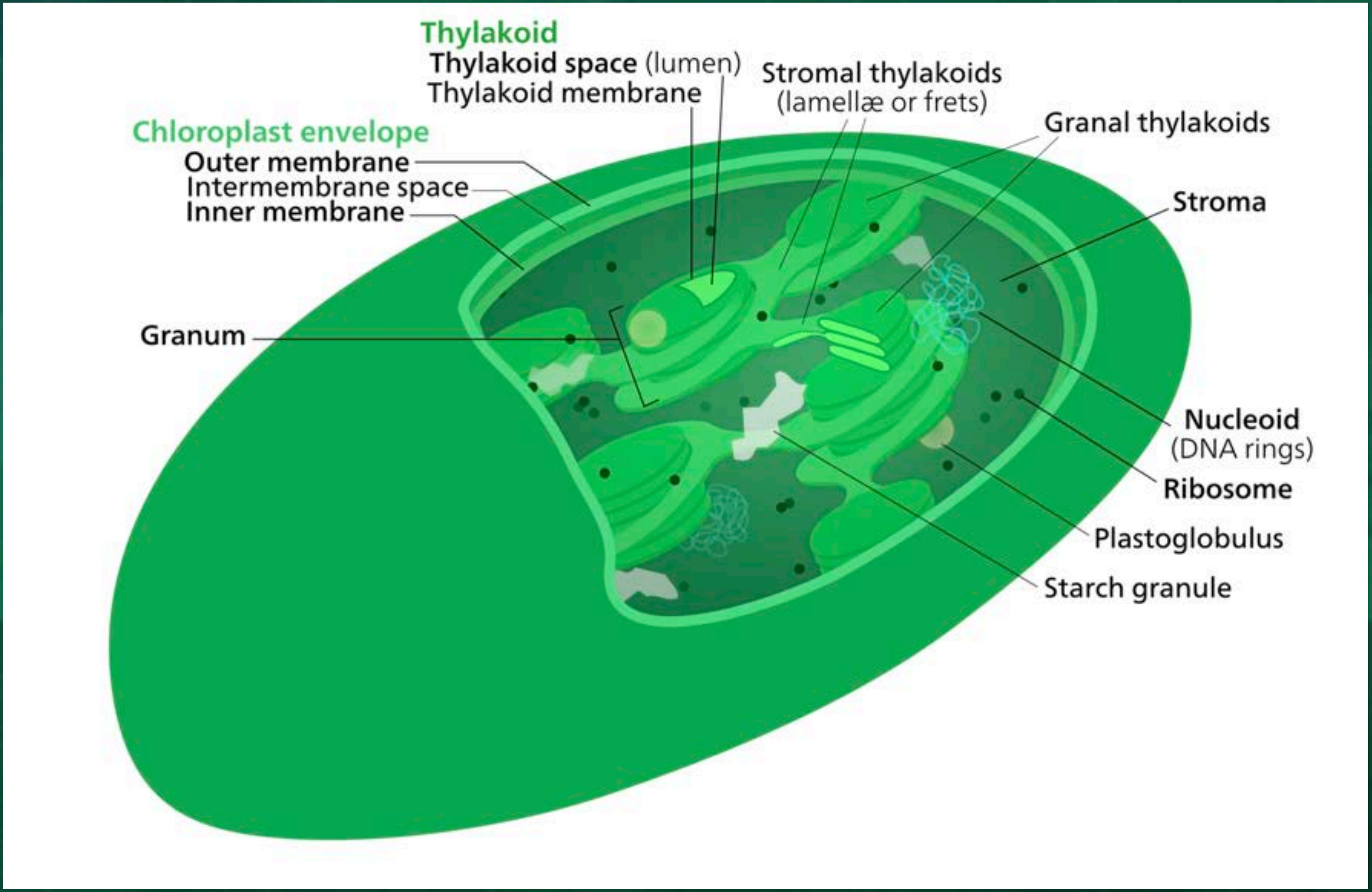
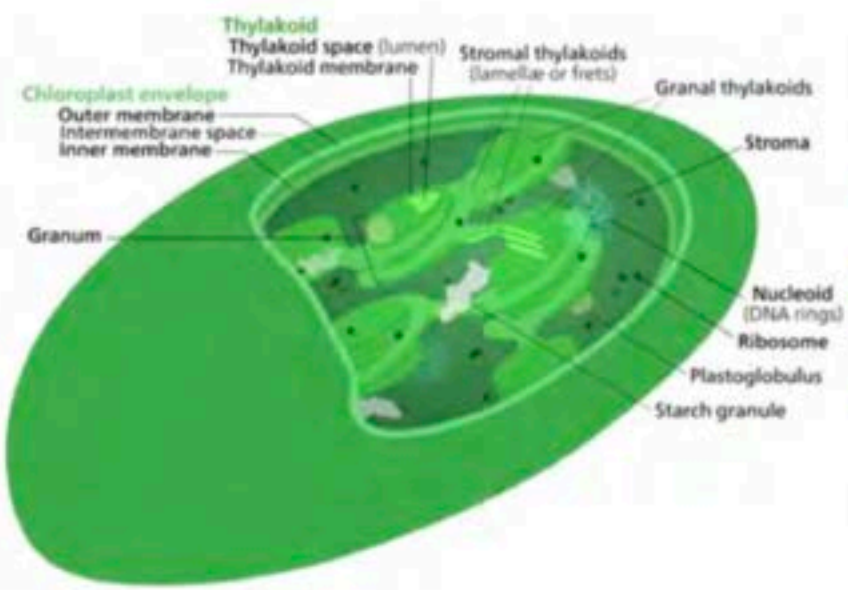
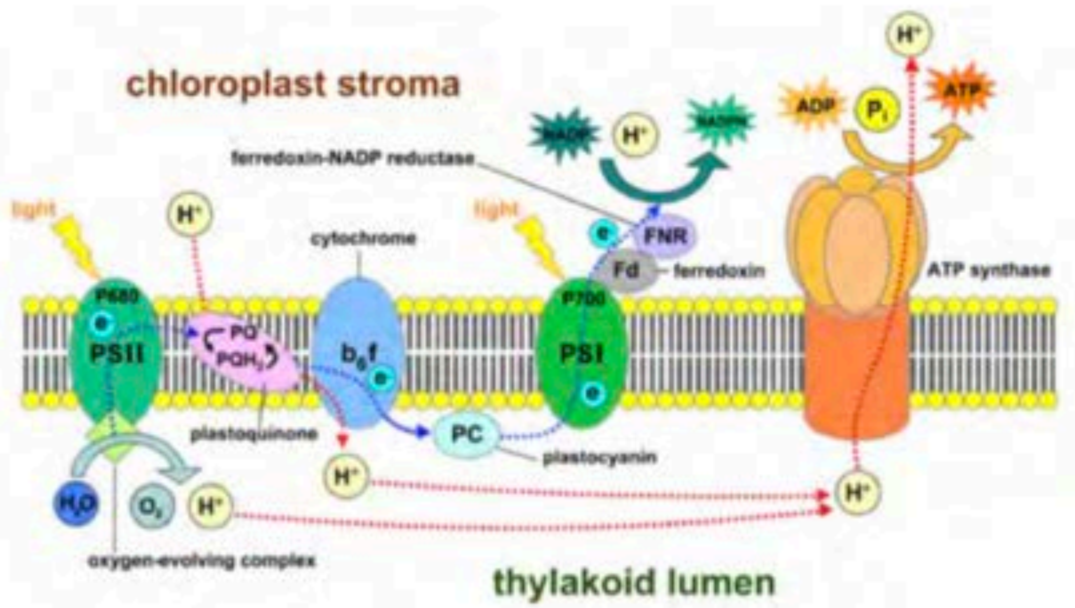
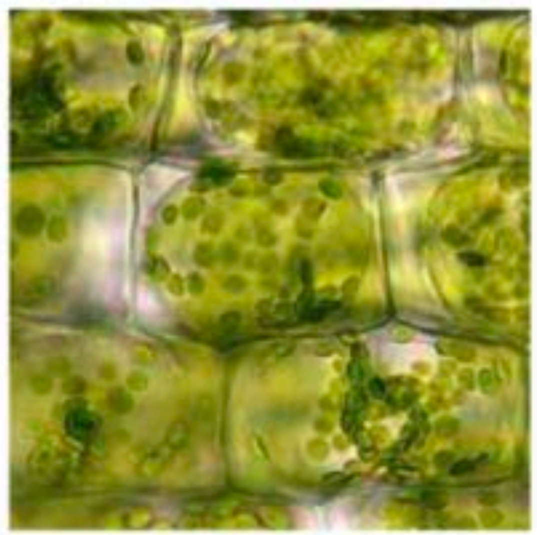

Thylakoid
Thylakoid space (lumen)
Thylakoid membrane
Stromal thylakoids
(lamellæ or frets)
Granal thylakoids
Chloroplast envelope
Outer membrane
Intermembrane space
Inner membrane
Stroma
Granum
Nucleoid
(DNA rings)
Ribosome
Plastoglobulus
Starch granule

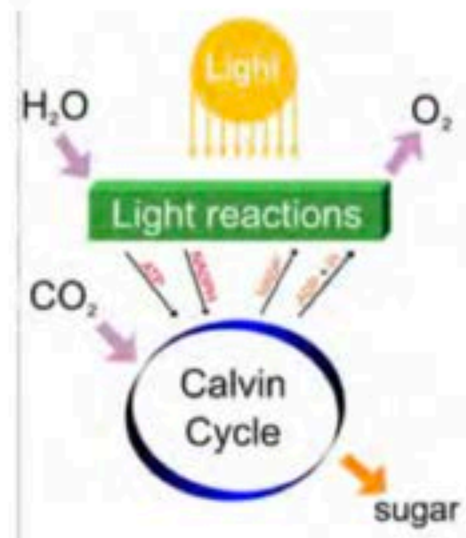
Realize that "*photosynthesis*" is better termed "*photophosphorylation*", because the energy of light is actually being used *not* to make sugar directly, but rather to *generate an H+ gradient across a membrane*. This drives phosphorylation of ADP to **ATP**, the energy currency of living systems. In other steps, the **ATP** is used to power the reactions of glucose production. Here's a view of activity on the chloroplast stromal membrane:





Here is the light-powered reaction sequence by which sugars are made from carbon dioxide and water:





$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} \xrightarrow{\text{Light}} \underset{\text{Sugar}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2}$$

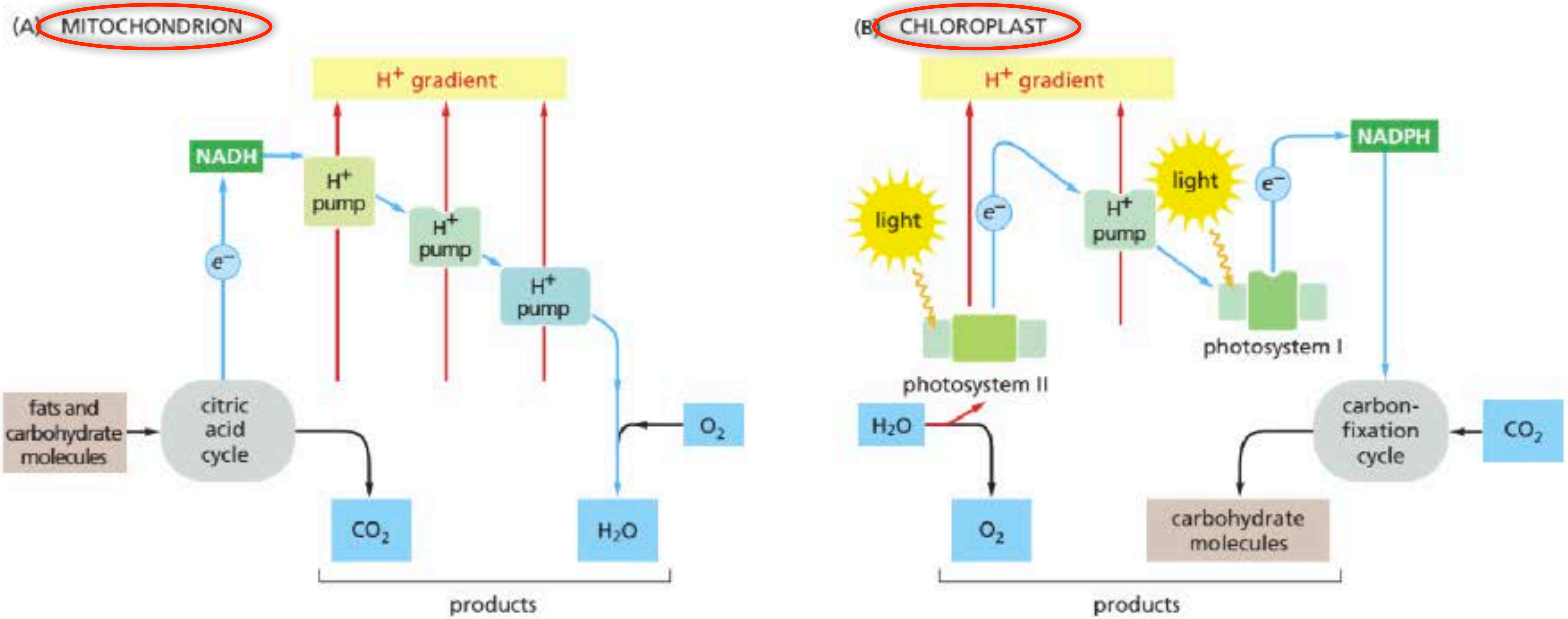
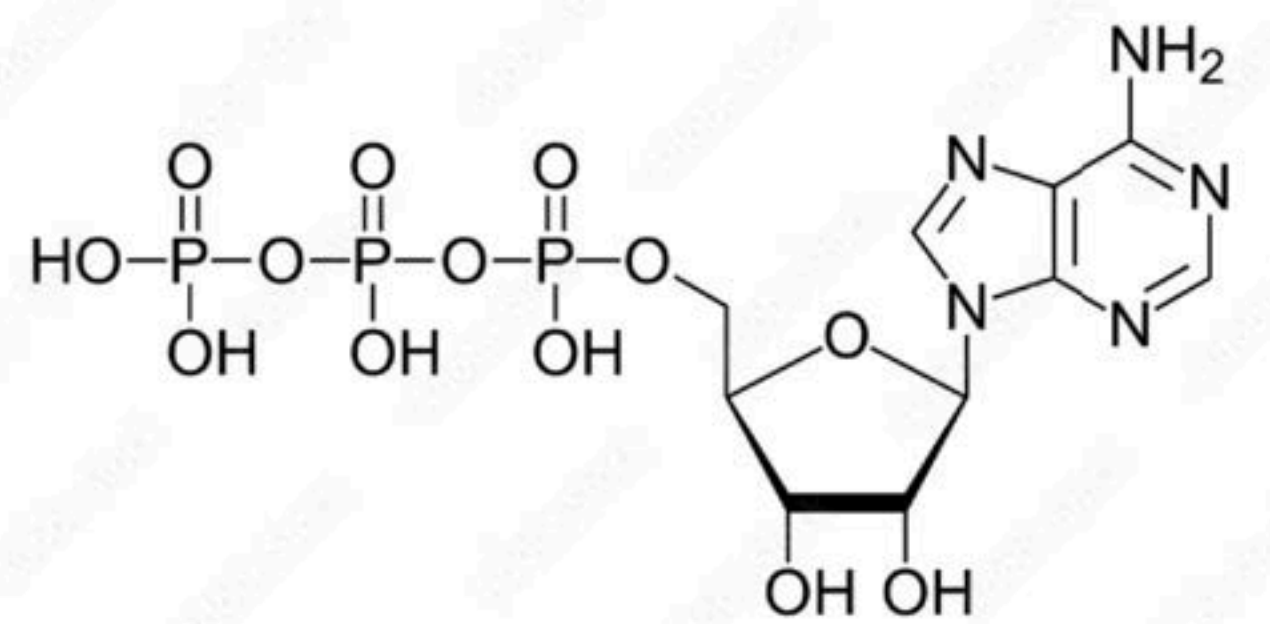
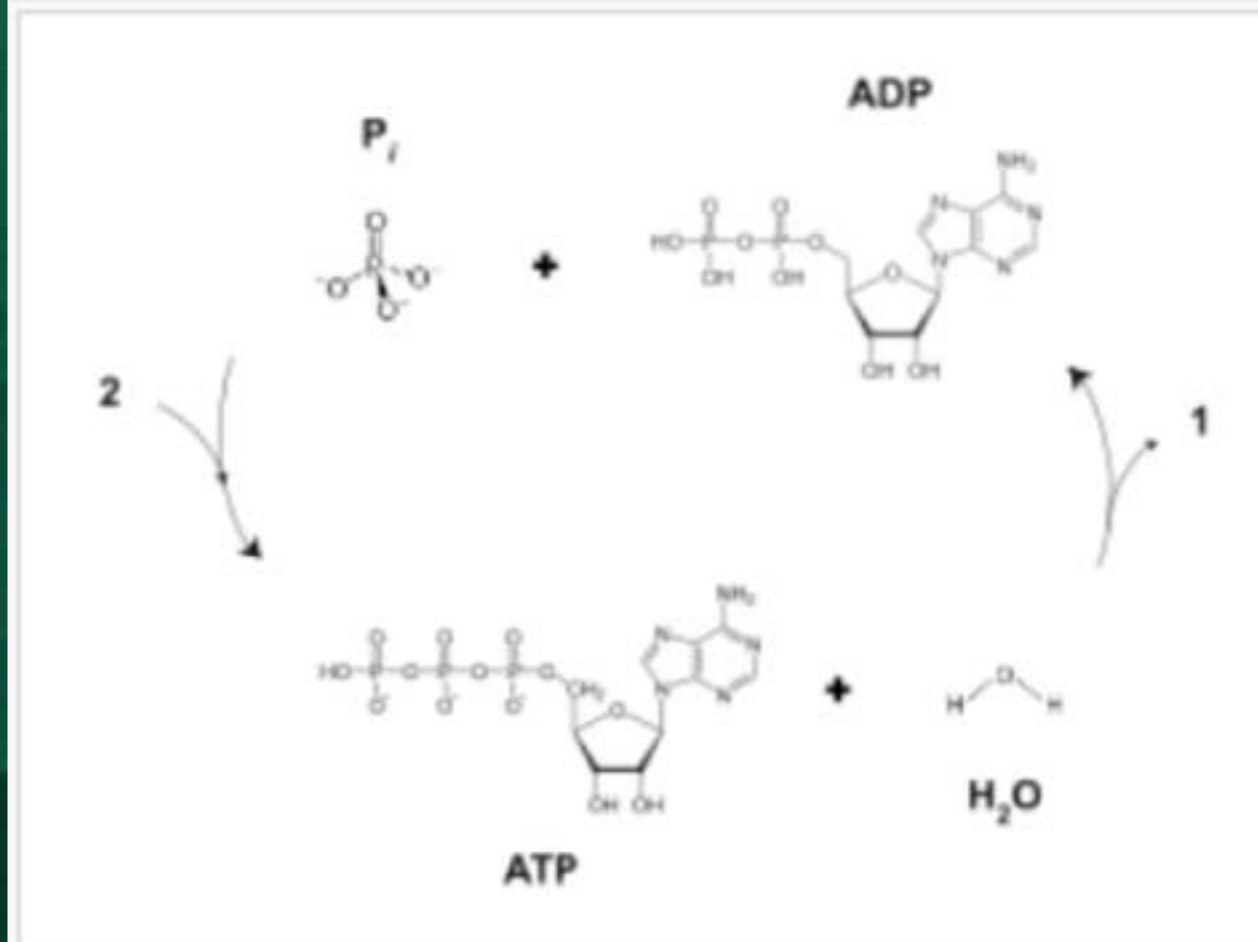


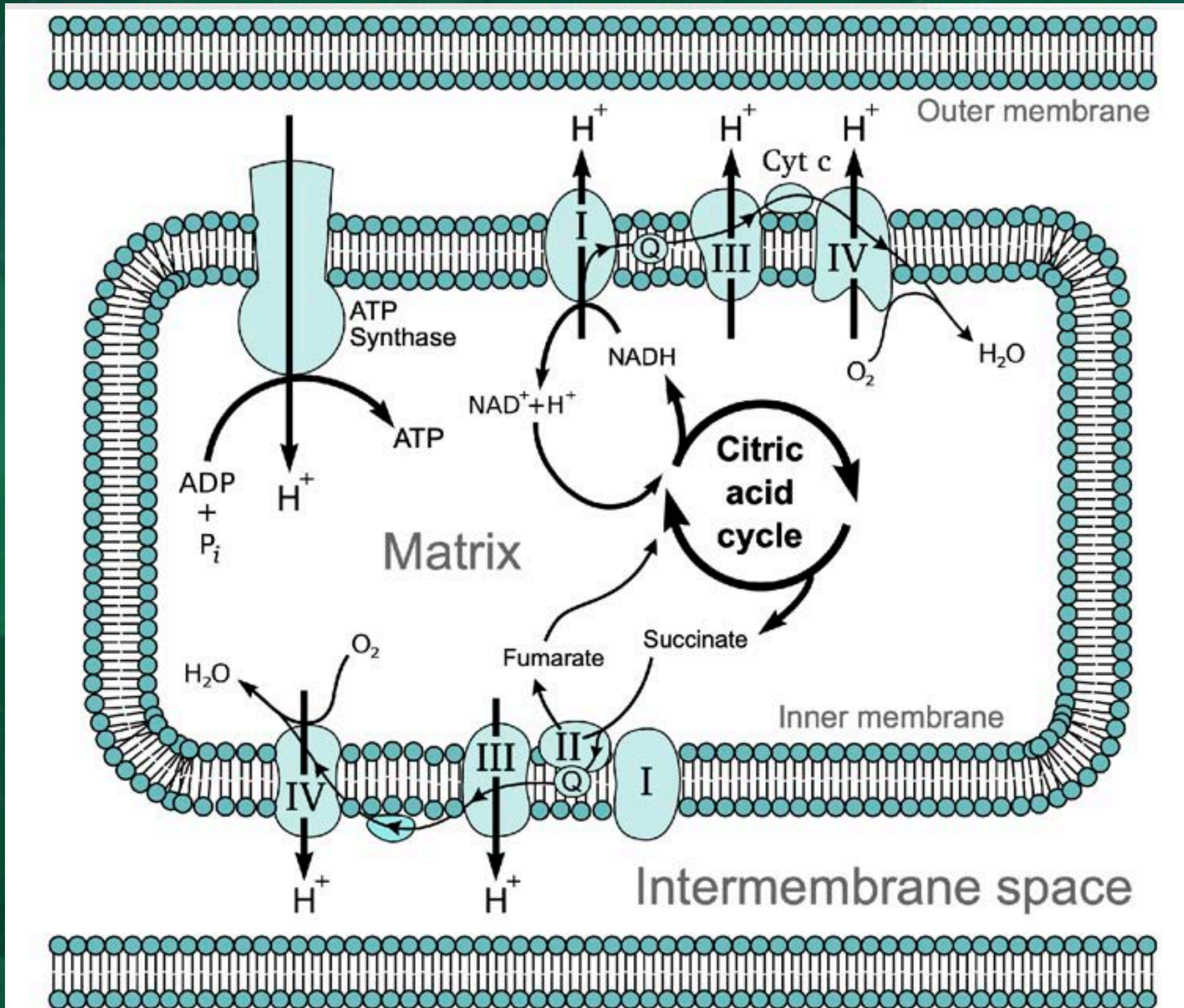
Figure 1–4 Electron-transport processes. (A) The mitochondrion converts energy from chemical fuels. (B) The chloroplast converts energy from sunlight. In both cases, electron flow is indicated by *blue arrows*. Each of the protein complexes *(green)* is embedded in a membrane. In the mitochondrion, fats and carbohydrates from food molecules are fed into the citric acid cycle and provide electrons to generate the energy-rich compound NADH from NAD^+. These electrons then flow down an energy gradient as they pass from one complex to the next in the electron-transport chain, until they combine with molecular O_2 in the last complex to produce water. The energy released at each stage is harnessed to pump H^+ across the membrane. In the chloroplast, by contrast, electrons are extracted from water through the action of light in the photosystem II complex and molecular O_2 is released. The electrons pass on to the next complex in the chain, which uses some of their energy to pump protons across the membrane, before passing to photosystem I, where sunlight generates high-energy electrons that combine with $NADP^+$ to produce NADPH. NADPH then enters the *carbon-fixation cycle* along with CO_2 to generate carbohydrates.



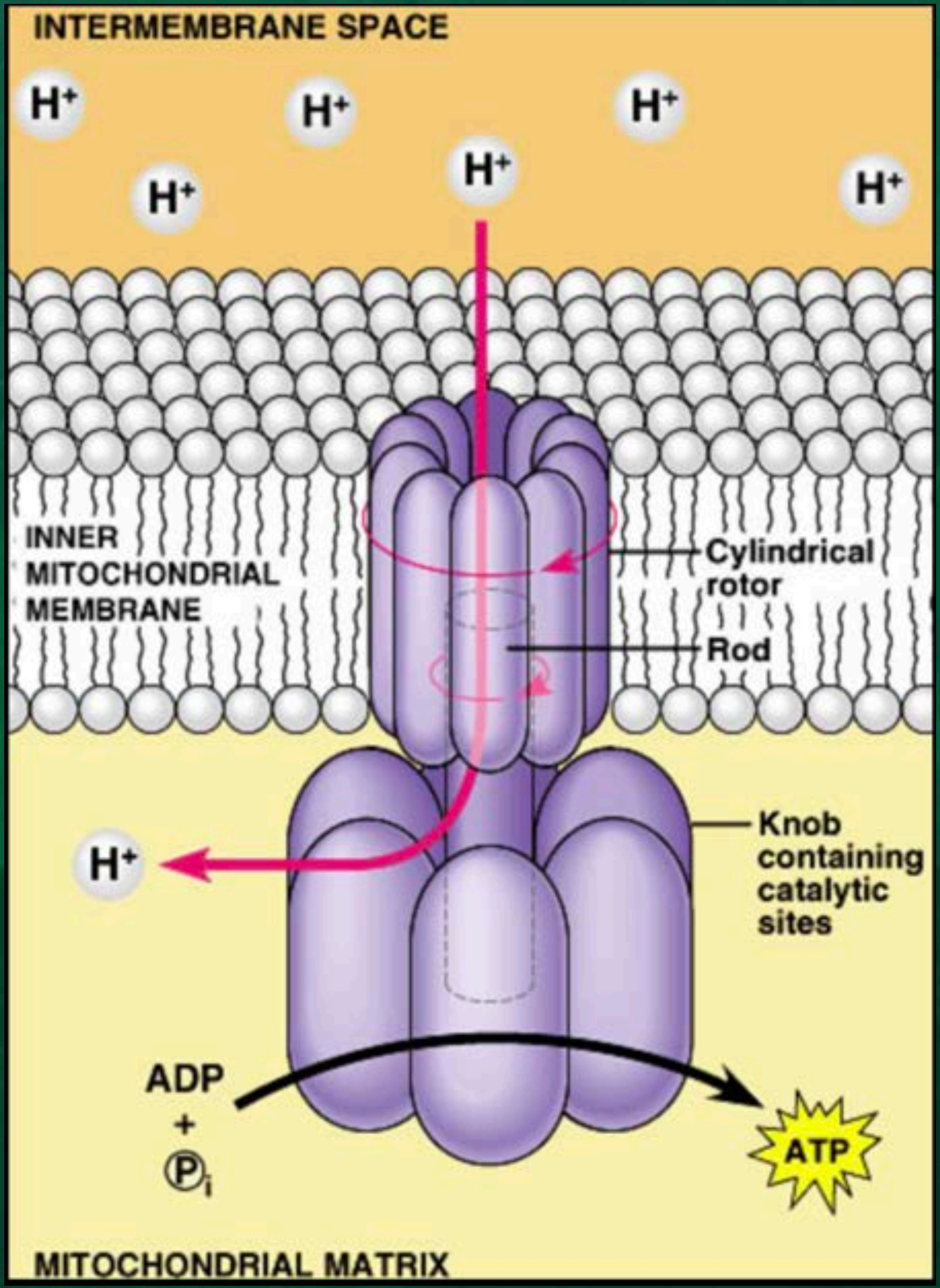
ATP
Adenosine triphosphate



The cycles of synthesis and degradation of ATP; 2 and 1 represent input and output of energy, respectively.



Outer membrane
H+
H+
H+
Cyt c
I
Q
III
IV
ATP
Synthase
NADH
H2O
O2
NAD+ + H+
ATP
Citric
acid
cycle
ADP
+
Pi
H+
Matrix
Succinate
Fumarate
O2
H2O
Inner membrane
II
III
Q
IV
I
H+
H+
Intermembrane space


INTERMEMBRANE SPACE
H+
INNER MITOCHONDRIAL MEMBRANE
Cylindrical rotor
Rod
Knob containing catalytic sites
ADP + Pi
ATP
MITOCHONDRIAL MATRIX

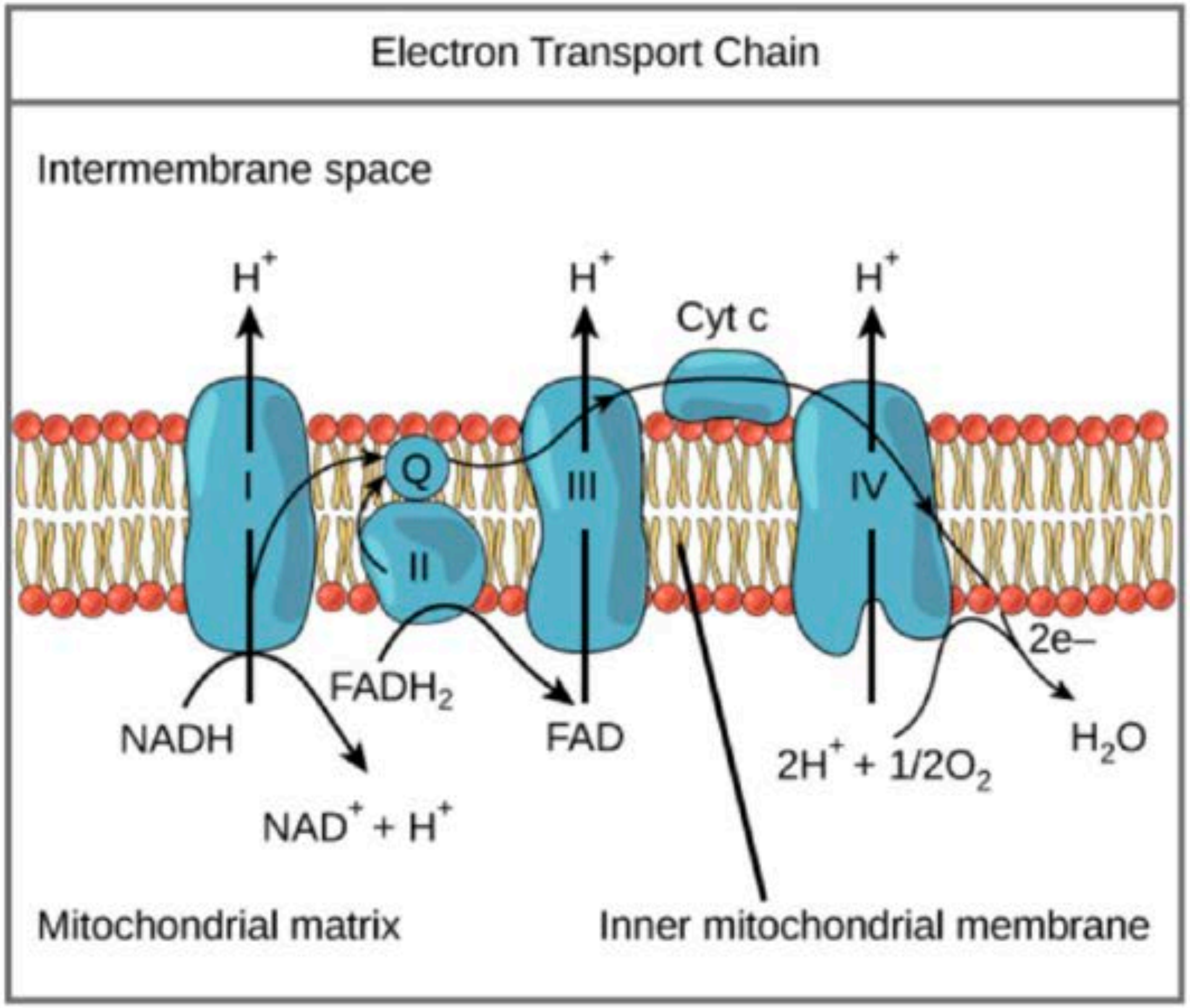
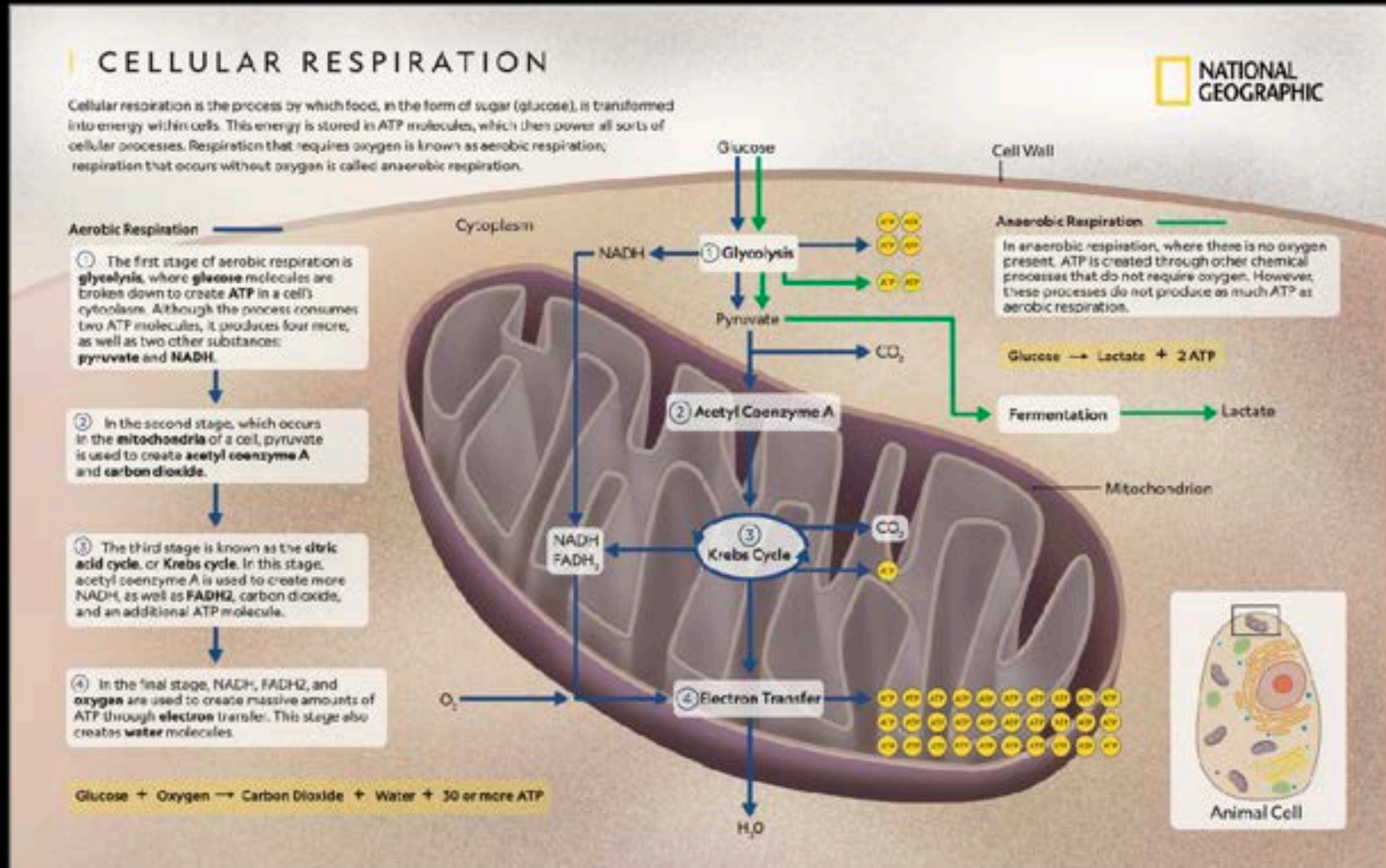


Figure 1. The electron transport chain is a series of electron transporters embedded in the inner mitochondrial membrane that shuttles electrons from NADH and $FADH_2$ to molecular oxygen. In the process, protons are pumped from the mitochondrial matrix to the intermembrane space, and oxygen is reduced to form water.

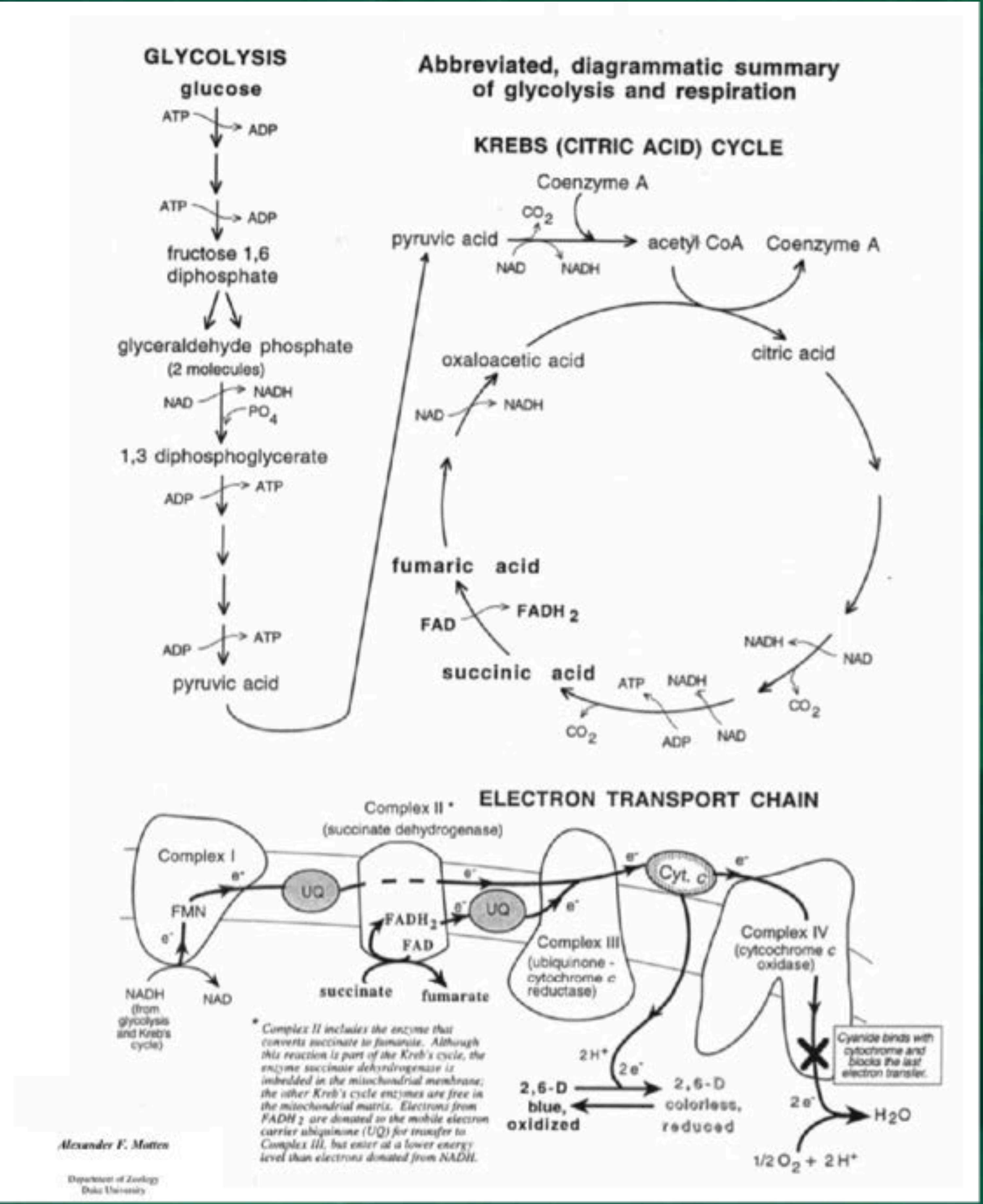


source

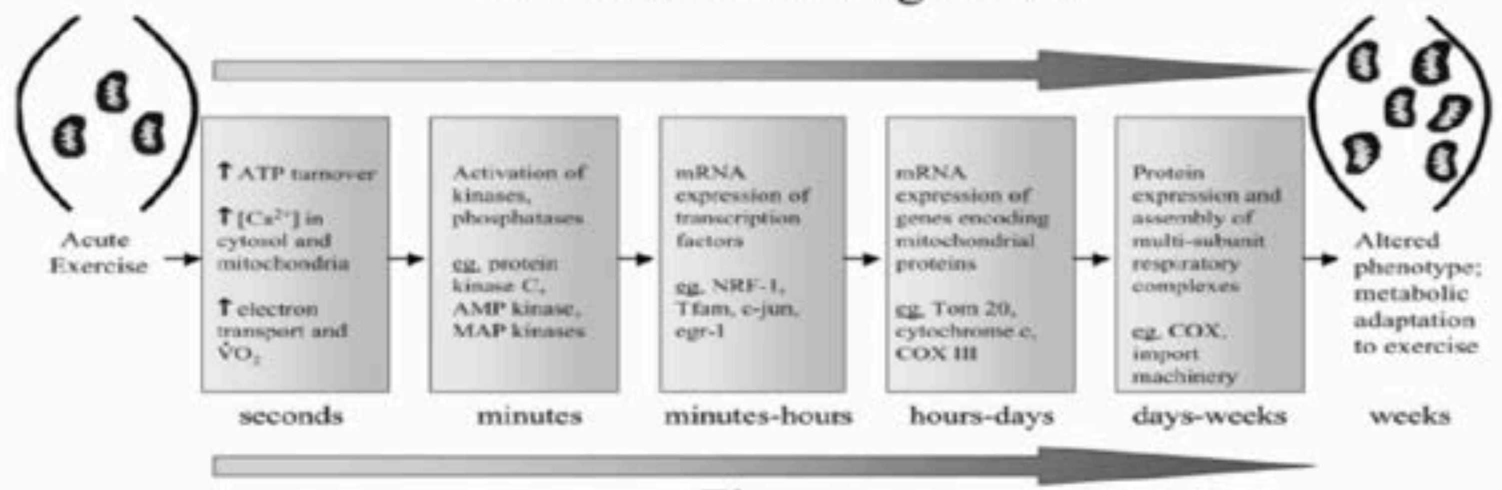
AEROBIC RESPIRATION

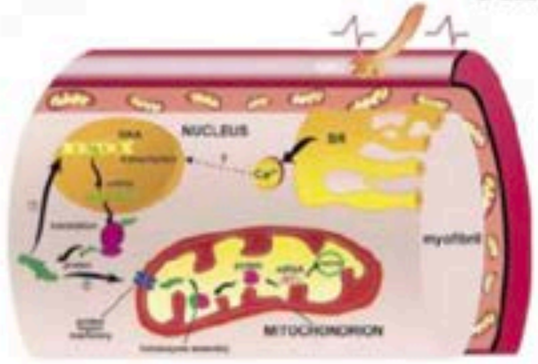
Aerobic respiration requires oxygen. This is the reason why we breathe oxygen in from the air. This type of respiration efficiently releases a large amount of energy from glucose that can be stored as ATP. Aerobic respiration happens all the time in animals and plants, where most of the reactions occur in the mitochondria. Even some prokaryotes can perform aerobic respiration (although since prokaryotes don't contain mitochondria, the reactions are slightly different). The overall chemical formula for aerobic respiration can be written as:

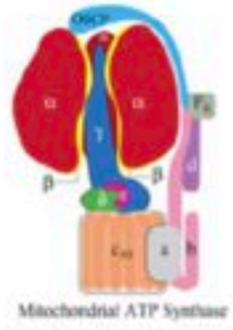
$C_6H_{12}O6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$ + (approximately) 38 ATP


GLYCOLYSIS
glucose
ATP
ADP
ATP
ADP
fructose 1,6 diphosphate
glyceraldehyde phosphate
(2 molecules)
NAD
NADH
PO4
1,3 diphosphoglycerate
ADP
ATP
ADP
ATP
pyruvic acid
Abbreviated, diagrammatic summary of glycolysis and respiration
KREBS (CITRIC ACID) CYCLE
Coenzyme A
CO2
pyruvic acid
NAD
NADH
acetyl CoA
Coenzyme A
citric acid
oxaloacetic acid
NAD
NADH
fumaric acid
FAD
FADH 2
succinic acid
ATP
NADH
CO2
ADP
NAD
NADH
NAD
CO2
ELECTRON TRANSPORT CHAIN
Complex II *
(succinate dehydrogenase)
Complex I
e-
FMN
e-
UQ
FADH2
FAD
UQ
e-
Cyt. c
Complex III
(ubiquinone - cytochrome c reductase)
Complex IV
(cytochrome c oxidase)
NADH
(from glycolysis and Kreb's cycle)
NAD
succinate
fumarate
2H+
2e-
2,6-D
blue,
oxidized
2,6-D
colorless,
reduced
Cyanide binds with cytochrome and blocks the last electron transfer.
2e-
H2O
1/2 O2 + 2H+
* Complex II includes the enzyme that converts succinate to fumarate. Although this reaction is part of the Kreb's cycle, the enzyme succinate dehydrogenase is imbedded in the mitochondrial membrane; the other Kreb's cycle enzymes are free in the mitochondrial matrix. Electrons from FADH 2 are donated to the mobile electron carrier ubiquinone (UQ) for transfer to Complex III, but enter at a lower energy level than electrons donated from NADH.
Alexander F. Motten
Department of Zoology
Duke University

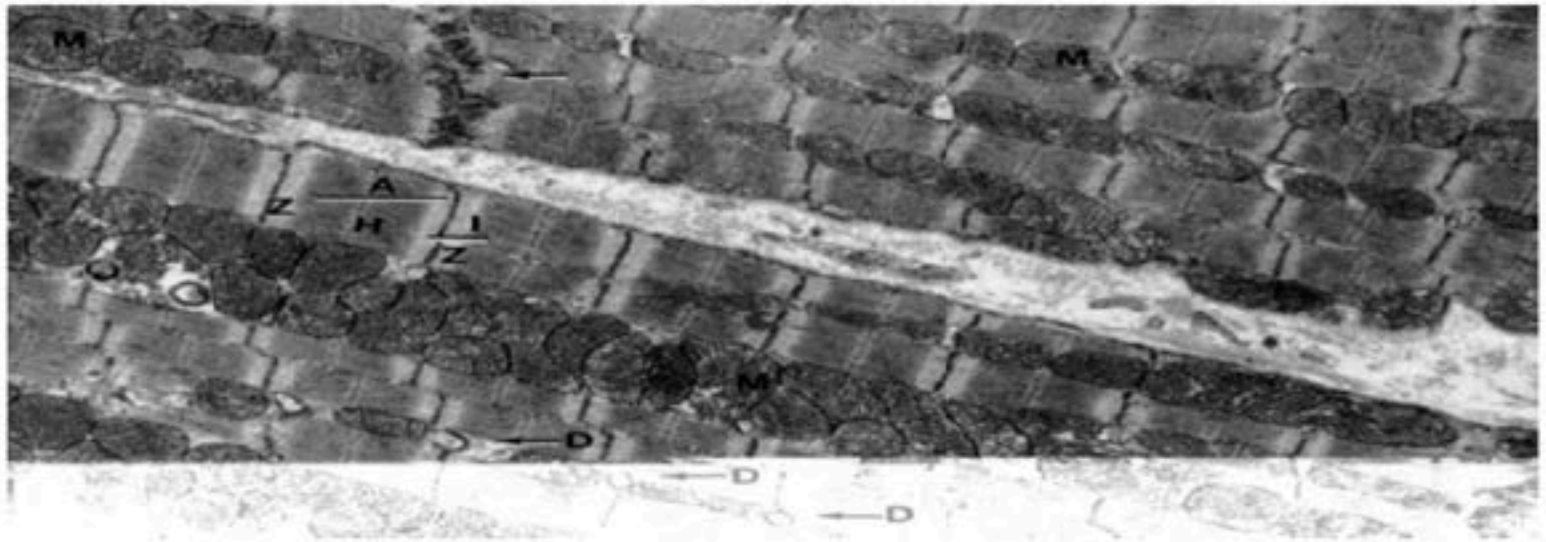
Established sequence of exercise-induced events leading to mitochondrial biogenesis

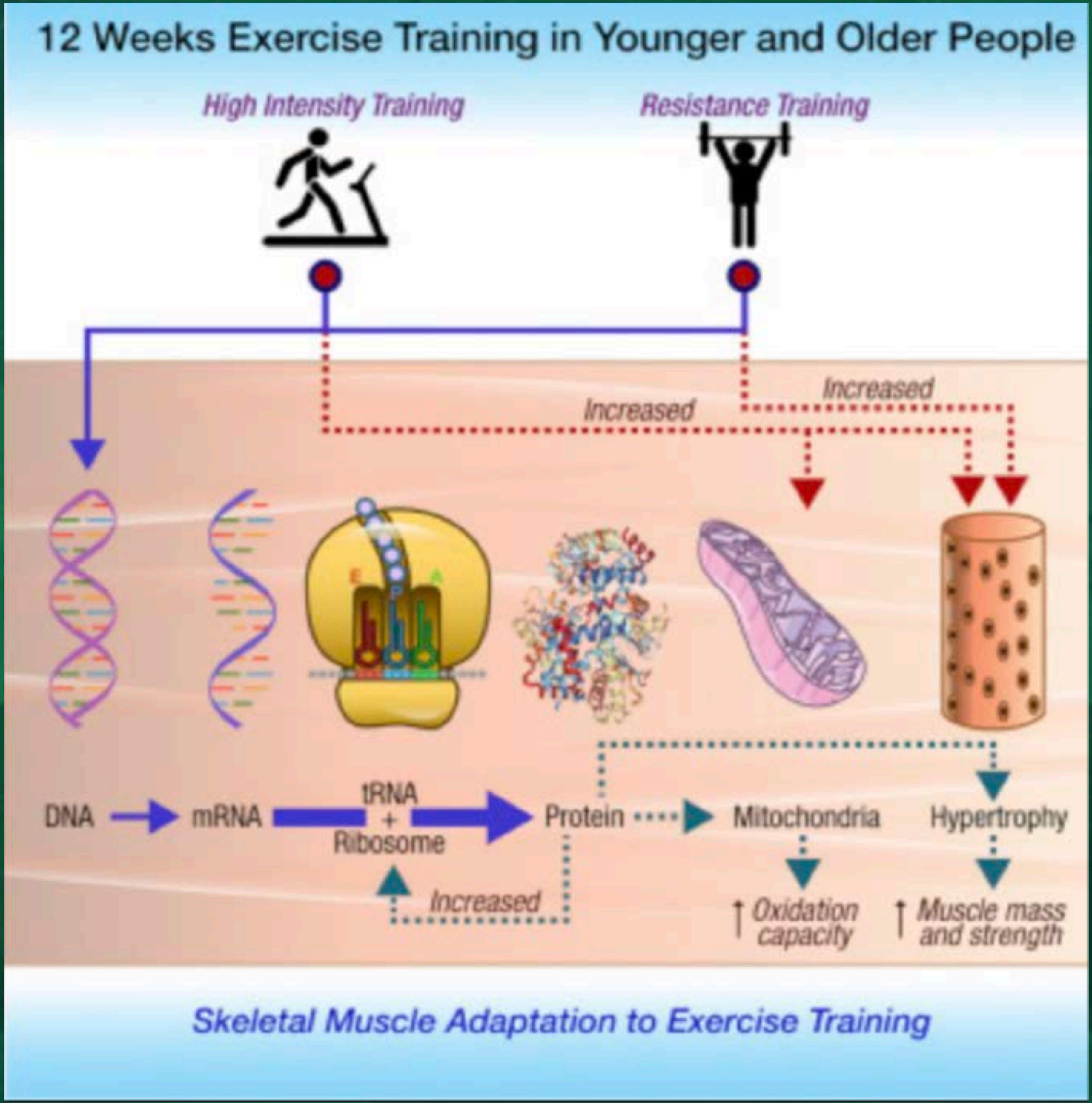


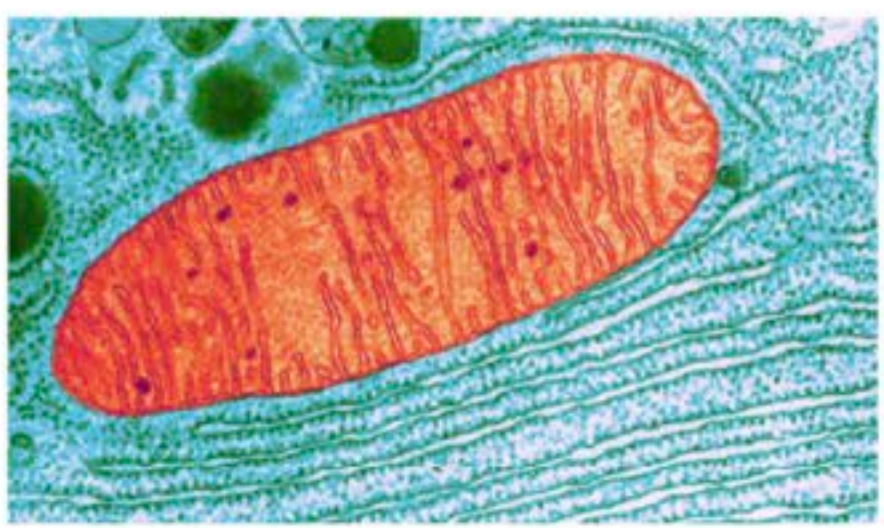


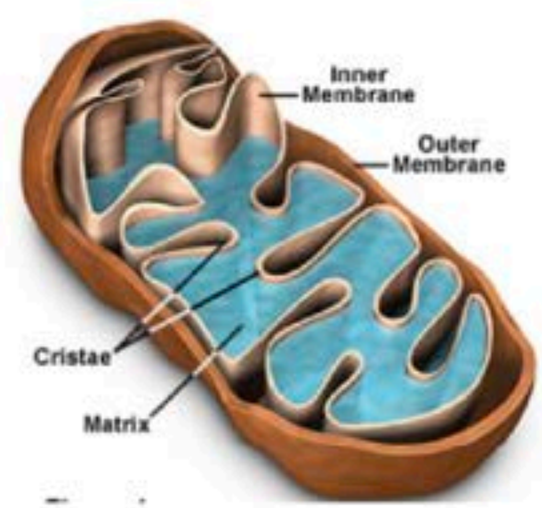


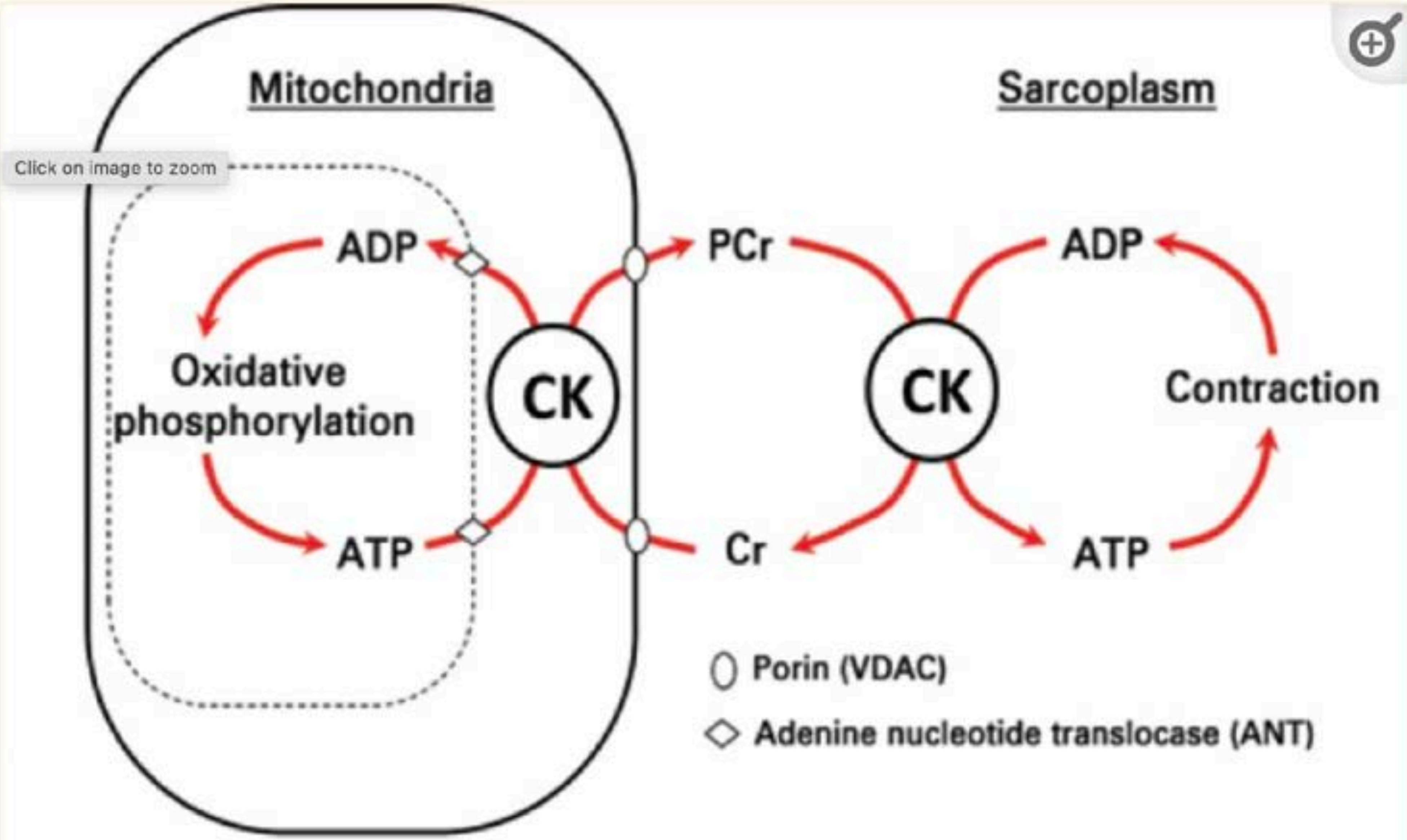
It is well known that endurance training, employing an appropriate duration per day, frequency per week, and submaximal intensity per exercise bout, can produce an increase in mitochondrial content, usually ranging from 50 to 100% within a 6 wk period. This directly results in improved endurance performance, largely independent of the much smaller training-induced changes in maximal oxygen consumption. *J Appl Physiol* **90: 1137–1157, 2001**




12 Weeks Exercise Training in Younger and Older People
High Intensity Training
Resistance Training
Increased
Increased
DNA
mRNA
tRNA
+
Ribosome
Protein
Mitochondria
Hypertrophy
Increased
↑ Oxidation capacity
↑ Muscle mass and strength
Skeletal Muscle Adaptation to Exercise Training




Inner Membrane
Outer Membrane
Cristae
Matrix



ADP: adenosine diphosphate; CK: creatinine kinase; PCr: phosphocreatine; ATP: adenosine triphosphate; Cr: free creatinine

Figure 1

Phosphocreatine "shuttle" system

CREATINE KINASE catalyzes the reversible transfer of phosphate between phosphocreatine (PCr) and ATP

$$Mg \cdot ADP + PCr + H^{+} \leftrightarrow Mg \cdot ATP + \text{creatine}$$

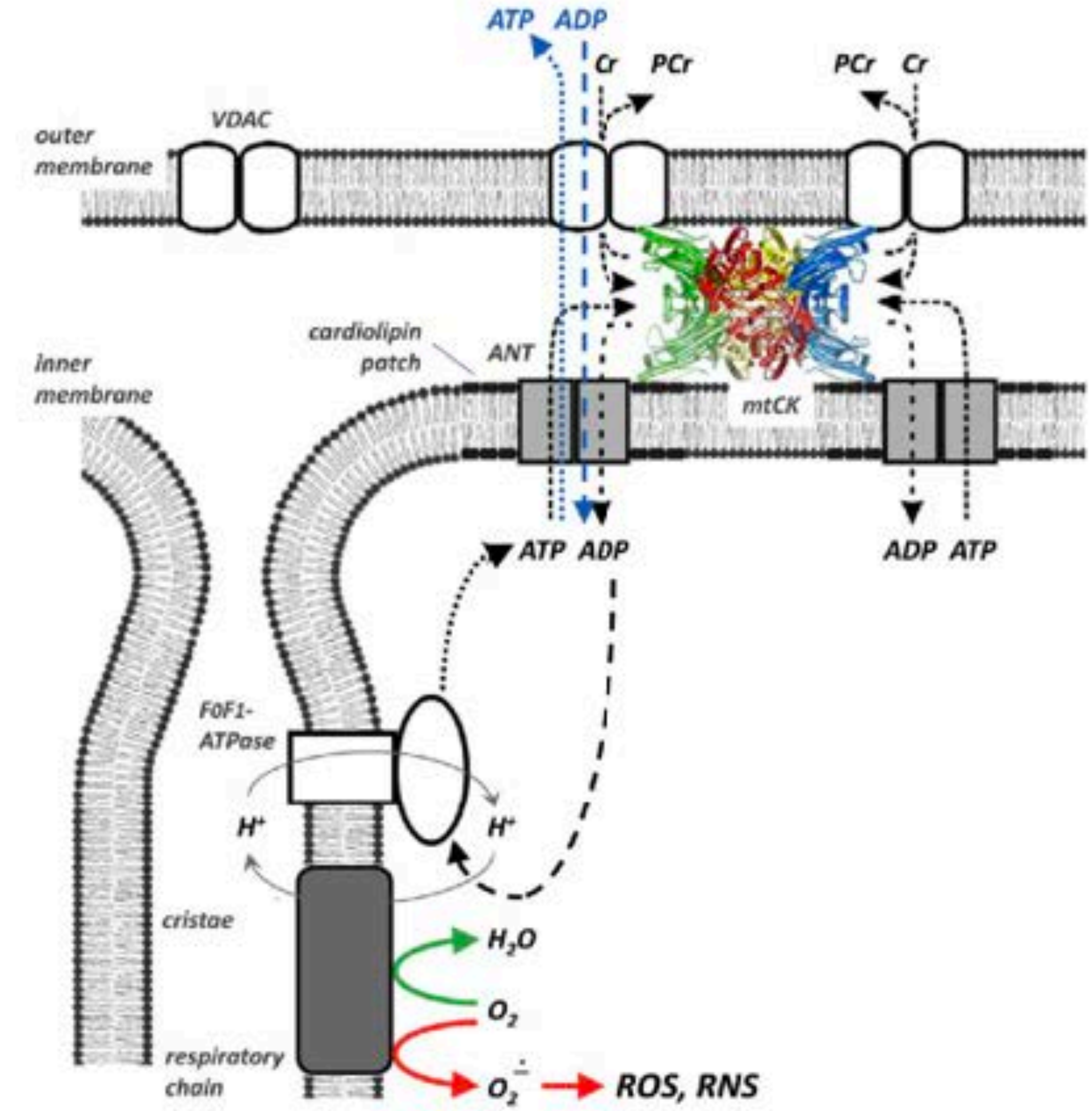
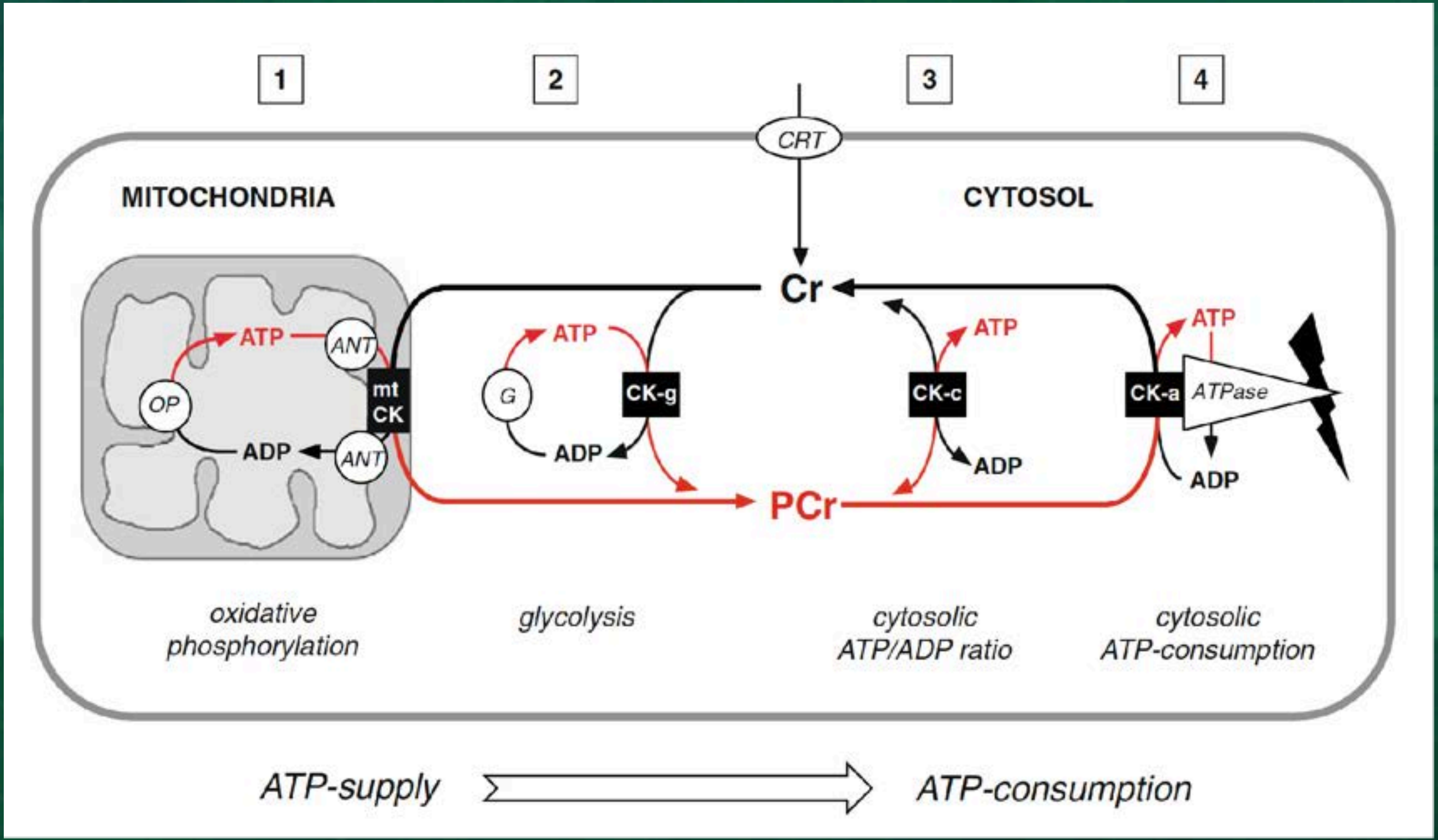
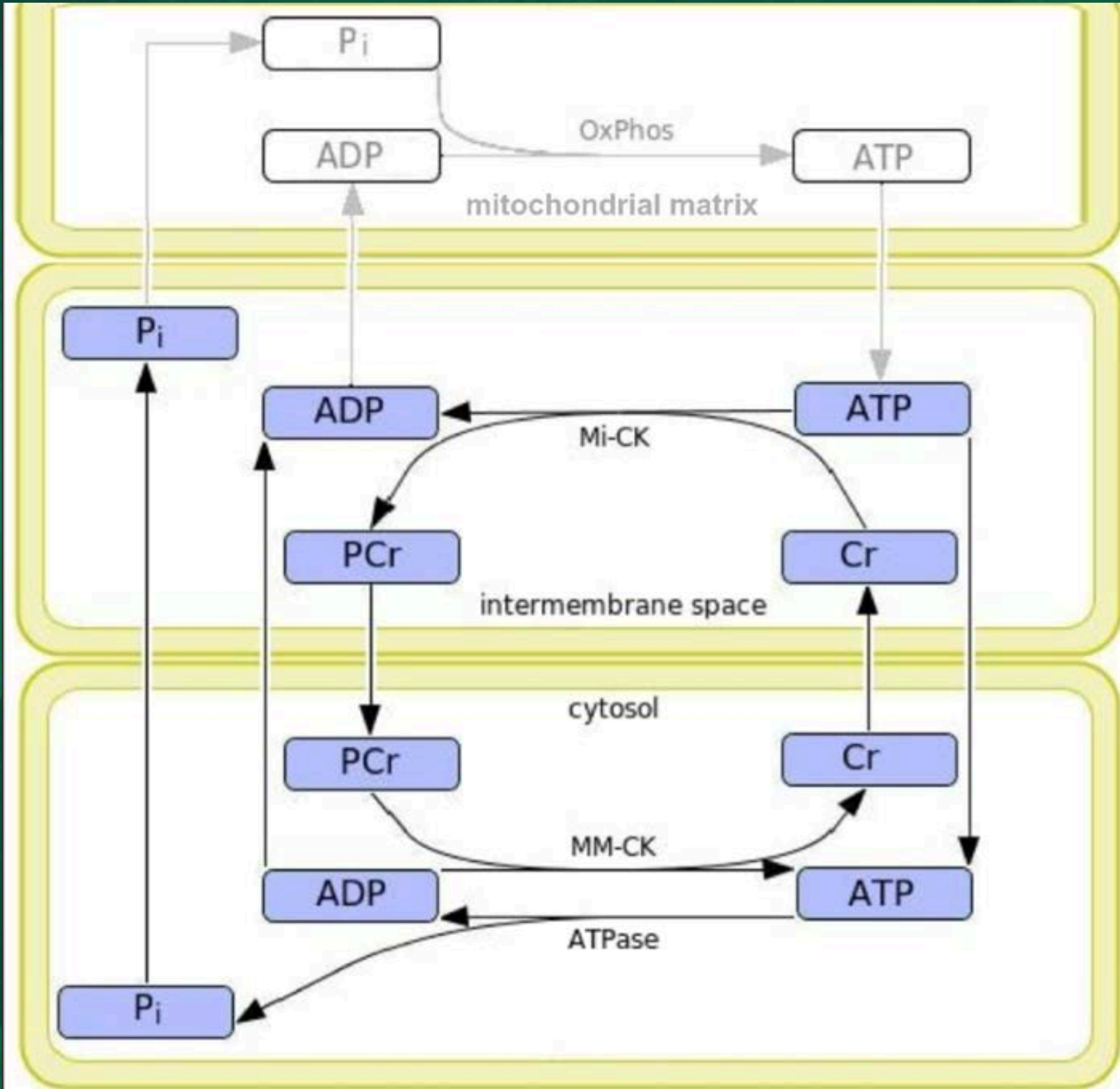
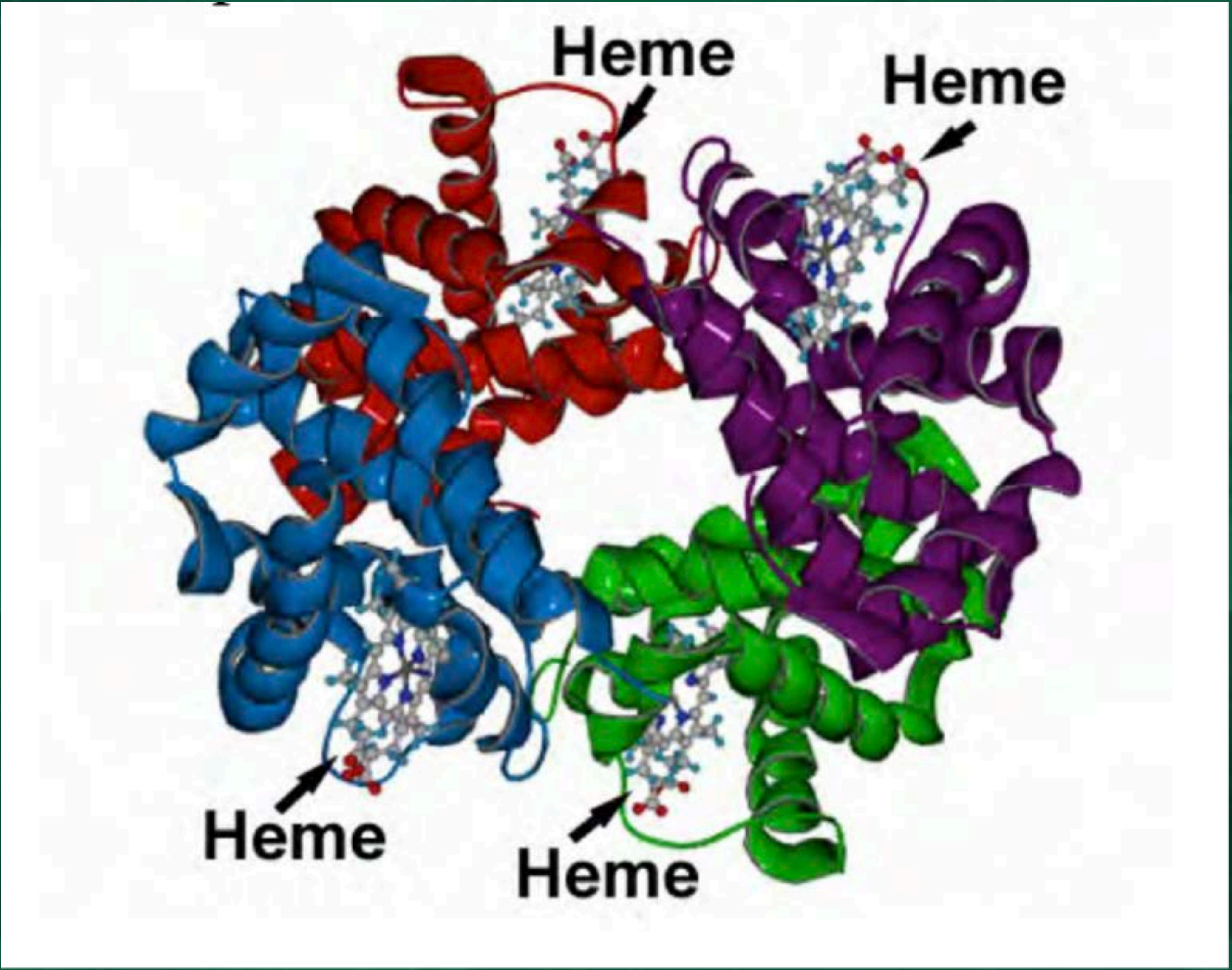
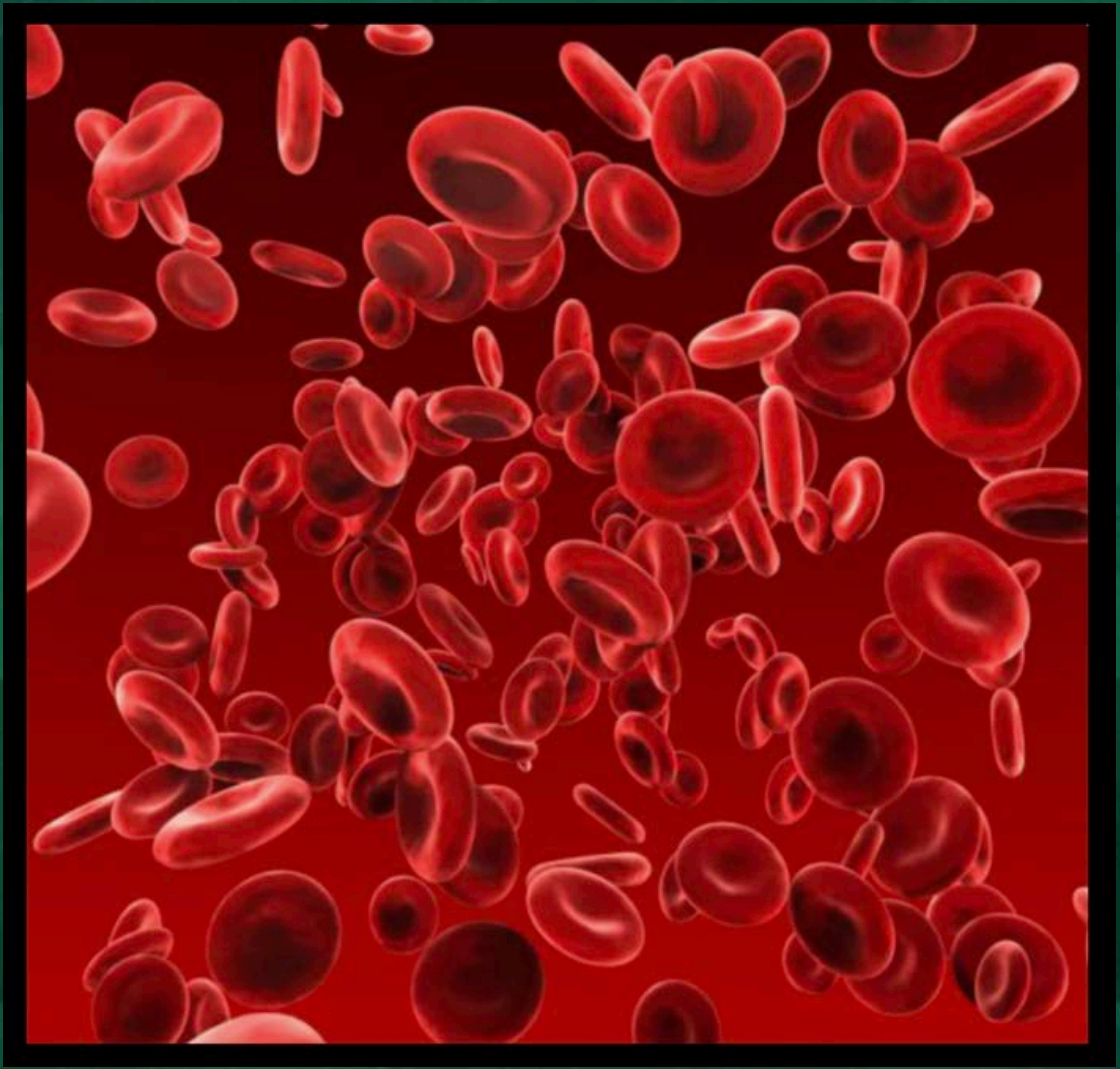


Fig. 3 Mitochondrial mtCK functions for high-energy metabolite channelling in mitochondria. In cells with oxidative metabolism, respiration (green arrow), ATP synthesis and ATP export through the inner mitochondrial membrane via adenine nucleotide transporter (ANT) are tightly coupled to trans-phosphorylation of ATP to PCr by mtCK and export of PCr into the cytosol by the outer membrane voltage-dependent anion channel (VDAC) as indicated by black arrows. In turn, Cr stimulates respiration by favoring constant supply of ADP to the matrix (black arrows), which also lowers ROS/RNS production in the intra-mitochondrial space (red arrows) and inhibits mitochondrial permeability transition. The tight coupling of substrate and product fluxes (black arrows) allows a so-called channeling of "high-energy" metabolites, with PCr being the one released into the cytosol, and ATP/ADP being mainly recycled within the mitochondria. The structural basis of these mtCK microcompartments are proteolipid complexes containing either VDAC, octameric mtCK and ANT in the peripheral intermembrane space (as shown) or octameric mtCK and ANT in the cristae (not shown). These proteolipid complexes are maintained by mtCK interactions with anionic phospholipids and VDAC in the outer membrane, and with cardiolipin and thus indirectly with cardiolipin-associated ANT in the inner membrane (see cardiolipoin patches). In cases of a less coupled mtCK microcompartment, e.g. after impairment of mtCK function by oxidative damage, there is partial direct ATP/ADP exchange with the cytosol (blue arrows). (Figure adapted from Kaldis et al. 1997; Meyer et al. 2006; Schlattner et al. 2006a; Schlattner et al. 2011) (The different fluxes are indicated by *coloured arrows* in the figure)


1
2
3
4
CRT
MITOCHONDRIA
CYTOSOL
Cr
ATP
ANT
OP
mt
CK
ADP
ANT
ATP
G
CK-g
ADP
ATP
CK-c
ADP
ATP
CK-a
ATPase
ADP
PCr
oxidative
phosphorylation
glycolysis
cytosolic
ATP/ADP ratio
cytosolic
ATP-consumption
ATP-supply
ATP-consumption


Pi
OxPhos
ADP
ATP
mitochondrial matrix
Pi
ADP
ATP
Mi-CK
PCr
Cr
intermembrane space
cytosol
PCr
Cr
MM-CK
ADP
ATP
ATPase
Pi


Heme
Heme
Heme
Heme



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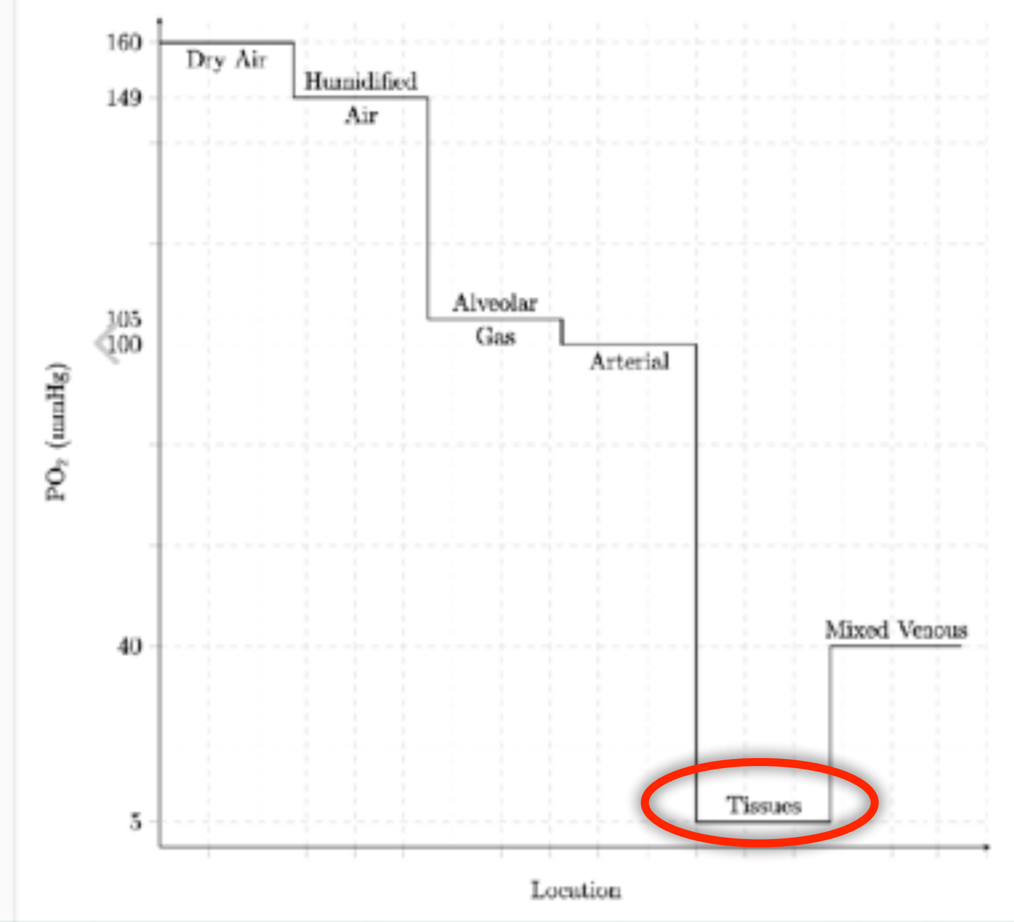
Oxygen Cascade

The **oxygen cascade** describes the transfer of oxygen from air to mitochondria.

- In each step of the cascade the PaO_2 falls
  It demonstrates that oxygen delivery to tissues relies on the **passive transfer** of gas down **partial pressure gradients**.
- The steps of the cascade are:
  - Dry atmospheric gas
  - Humidified tracheal gas
  - Alveolar gas
  - Arterial blood
  - Mitochondria
  - Venous blood



Atmospheric Gas

Atmospheric partial pressure of oxygen is a function of barometric pressure and the FiO_2:

- $PO_2 = P_B \times FiO_2$, where:
  - P_B is 760mmHg
  - FiO_2 is 0.21
- Therefore, PO_2 = **160mmHg**

PI_{N2}: 590 mmHg
PI_{O2}: 160 mmHg
PI_{Ar}: 7 mmHg
PI_{CO2}: 0.3 mmHg

PI_{O2}: 160 mmHg

Alveolar Gas

Ideal alveolar PO_2 is calculated using the **alveolar gas equation**:

$P_AO_2 = P_iO_2 - \frac{P_aCO_2}{R} + F$, where:

- P_AO_2 is the alveolar partial pressure of oxygen
- P_iO_2 is the inspired partial pressure of oxygen
- P_aCO_2 is the arterial partial pressure of carbon dioxide
- R is the respiratory quotient, where
  $R = \frac{\text{Volume of } CO_2 \text{ produced}}{\text{Volume of } O_2 \text{ consumed}}$

tracheal humidity 149 mmHg

respiratory PaCO2 → ↓ PaO2

Arterial Blood

- Normal arterial PO_2 is 100mmHg

PaO2: 100 mmHg

Mitochondria

- PO_2 varies with metabolic activity, but typically quoted as 5mmHg
- The **Pasteur point** is the partial pressure of oxygen at which oxidative phosphorylation ceases, and is **~1mmHg**

PaO2: 5 mmHg

Venous Blood

- PO_2 is greater than mitochondrial PO_2
  Mixed venous blood typically quoted as 40mmHg.
- Higher than mitochondria as not all arterial blood travels through capillary beds

PaO2: 40mmHg

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MAYO CLINIC

The Oxygen Cascade During Exercise in Health and Disease

Check for updates

Paolo B. Dominelli, PhD; Chad C. Wiggins, PhD; Tuhin K. Roy, PhD, MD; Timothy W. Secomb, PhD; Timothy B. Curry, PhD, MD; and Michael J. Joyner, MD

Abstract

The oxygen transport cascade describes the physiological steps that bring atmospheric oxygen into the body where it is delivered and consumed by metabolically active tissue. As such, the oxygen cascade is fundamental to our understanding of exercise in health and disease. Our narrative review will highlight each step of the oxygen transport cascade from inspiration of atmospheric oxygen down to mitochondrial consumption in both healthy active males and females along with clinical conditions. We will focus on how different steps interact along with principles of homeostasis, physiological redundancies, and adaptation. In particular, we highlight some of the parallels between elite athletes and clinical conditions in terms of the oxygen cascade.

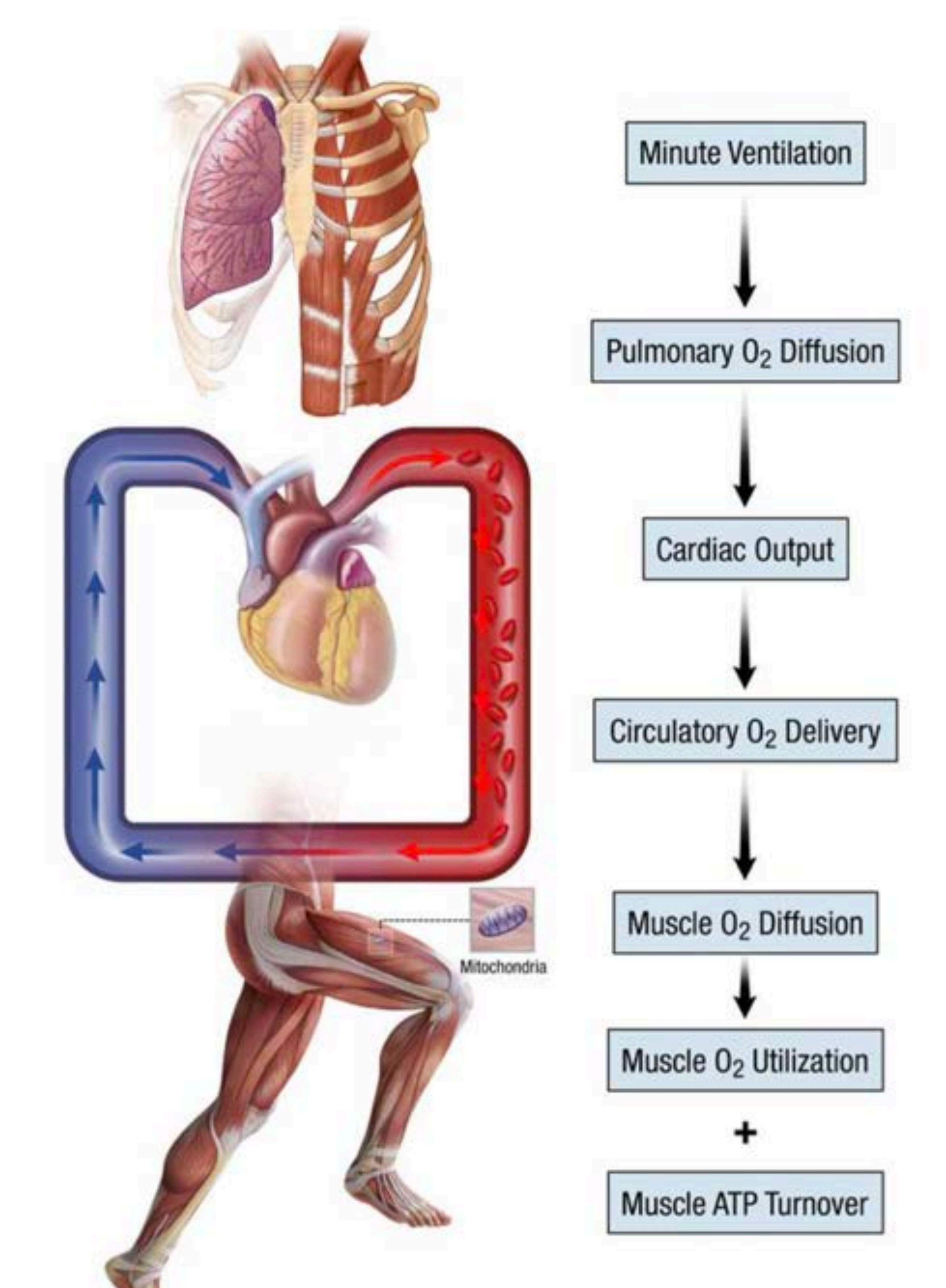
 ■ Mayo Clin Proc. 2021;96(4):1017-1032

In the era of molecular biology it is easy to overlook the central role that the oxygen molecule plays in life. In complex organisms, where most cells are anatomically remote from atmospheric oxygen, a transport and gas exchange system is required to move oxygen from the air to the tissues and supports the continuous generation of adenosine triphosphate via oxidative metabolism. To defend whole body homeostasis, this system must be robust enough to sustain vast increases in oxidative metabolism during exercise, survive at high altitude, and — at the opposite end of the homeostatic spectrum — withstand substantial insults to key elements of the system associated with disease. In this review, we will follow the movement of oxygen from the air to the tissues and use examples ranging from elite athletes, rare patients, and comparative biology to show key principles of oxygen transport in humans. The impressive adaptive nature of the cardiopulmonary system will be emphasized and the redundant nature of physiological control mechanisms and related anatomical design features will be highlighted.

THE PROBLEM

The partial pressure of oxygen in air at sea level is ~150 mm Hg, but in the mitochondria of exercising skeletal muscle the partial pressure of oxygen can be ~100-fold lower without significant engagement of anaerobic energy metabolism. Thus, the question is, how does this happen and what systems are engaged as it occurs? In this context, it is also important to consider the range of oxygen consumption that can be seen in humans. In healthy young adults, resting metabolic rate is approximately 3.5 mL $O_2 \cdot kg^{-1}$ of body weight $\cdot$ min^{-1} and it can increase to more than 90 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$ in at least some of the most aerobically trained elite athletes.[1] At the opposite end of the O_2 uptake spectrum, even modest metabolic rates require physiological redundancies to be engaged in patients with diseases that hinder the ability to take up, transfer, and utilize oxygen. Notable examples include marked tachypnea or tachycardia even during very modest levels of exercise in patients with diseases, such as chronic obstructive pulmonary disease or congestive heart failure, along with a marked redistribution of blood flow away from inactive tissues to the active muscles.[2]

From the Department of Kinesiology, University of Waterloo, Ontario, Canada (P.B.D.); Department of Anesthesiology and Perioperative Medicine, Mayo Clinic, Rochester, MN (C.C.W., T.K.R., T.B.C., M.J.J.); and the Departments of Physiology and Mathematics, University of Arizona, Tucson (T.W.S.).



The Oxygen Cascade During Exercise in Health and Disease
Mayo Clin Proc. 2021 April ; 96(4): 1017–1032.

- **The partial pressure of oxygen in air at sea level is ~150 mmHg but _in the mitochondria of exercising skeletal muscle_ the partial pressure of oxygen can be ~100-fold lower without significant engagement of anaerobic energy metabolism.**

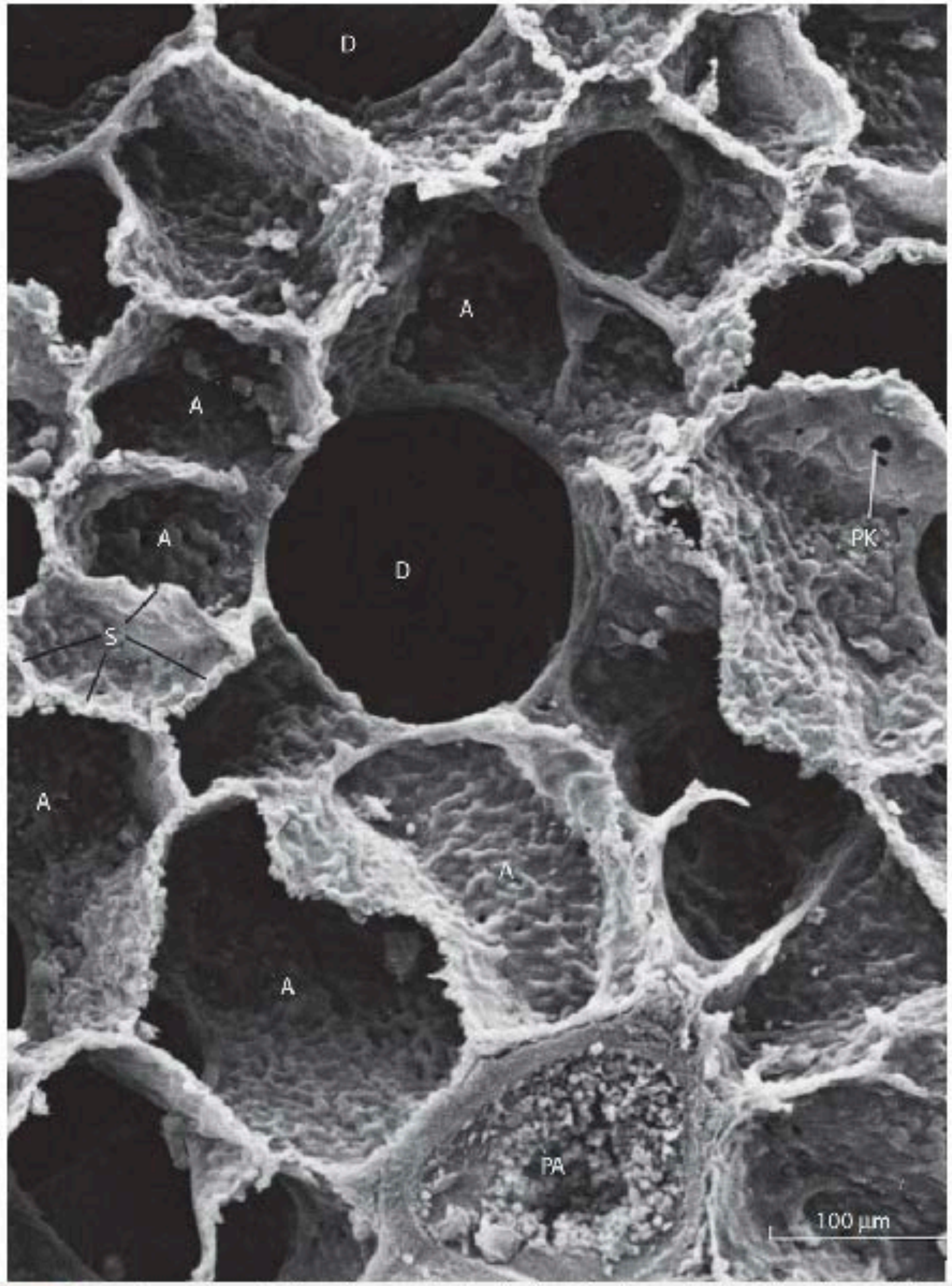


Figure 1–3. Scanning electron micrograph of human lung parenchyma. A = alveolus; S = alveolar septa; D = alveolar duct; PK = pore of Kohn; PA = small branch of the pulmonary artery. (Reproduced with permission from Fishman AP, Kaiser LR, Fishman JA, et al: *Pulmonary Diseases and Disorders*, 3rd ed. New York: McGraw-Hill; 1998.)

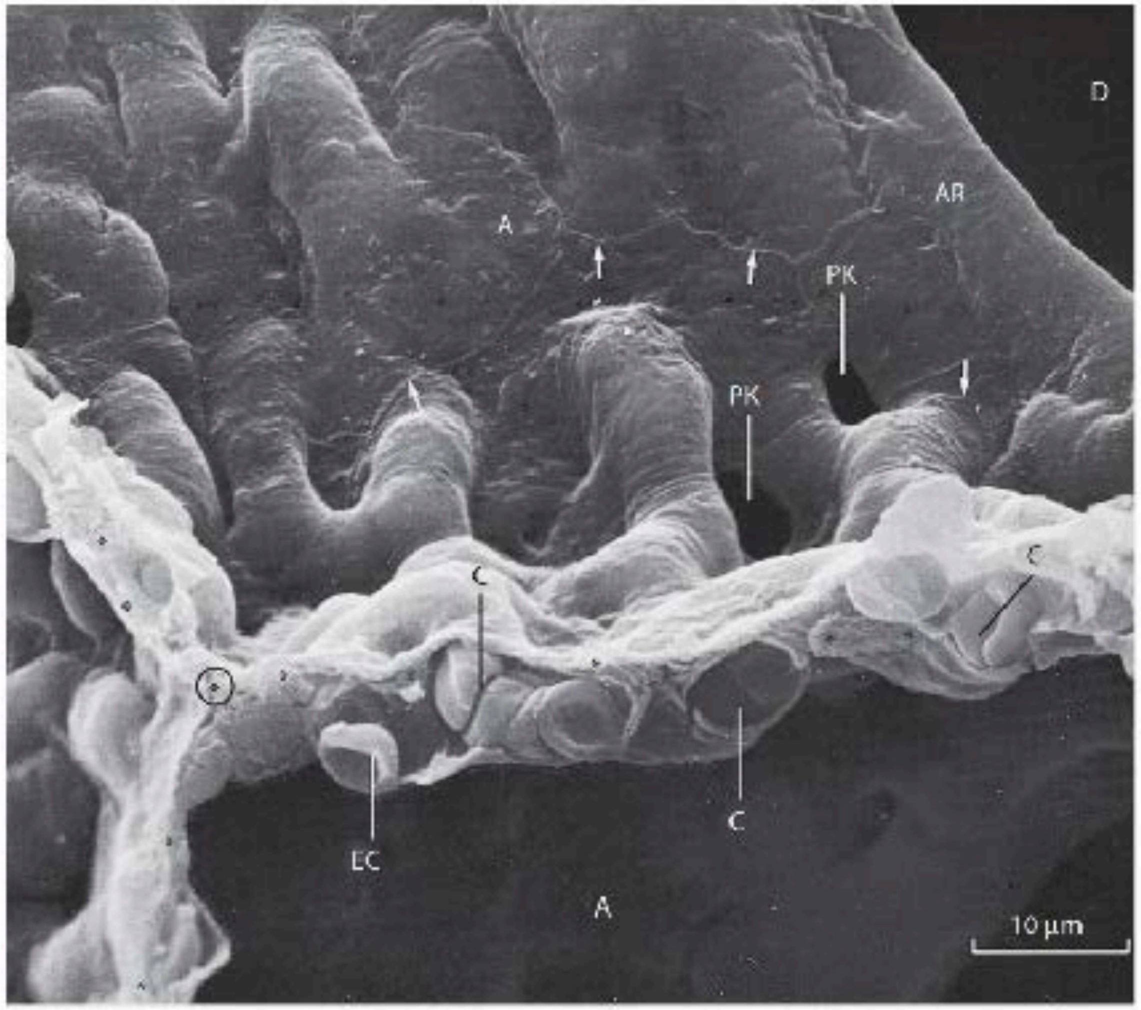


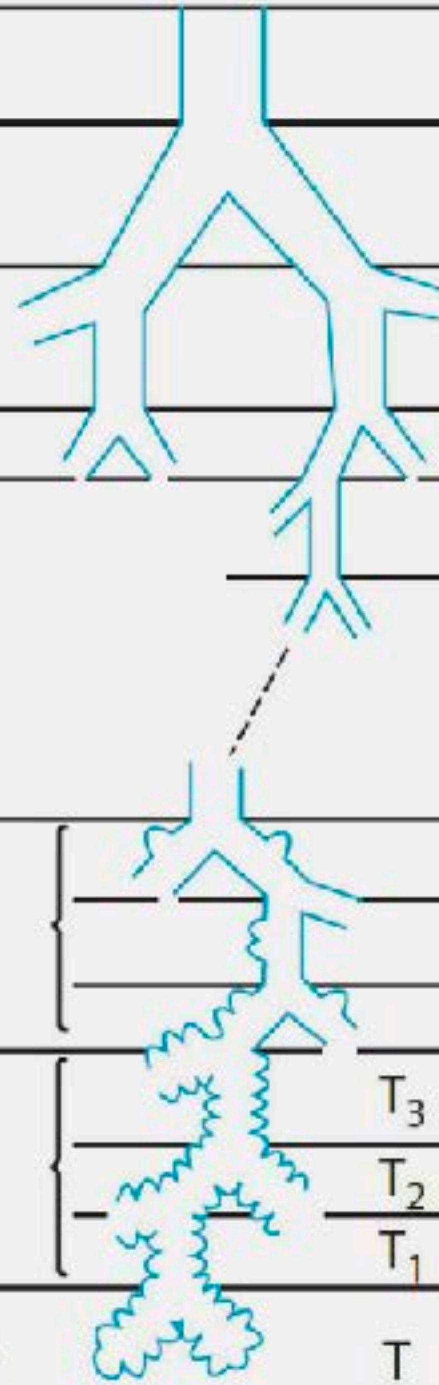
Figure 1–4. Scanning electron micrograph of the surface and cross section of an alveolar septum. Capillaries (C) are seen sectioned in the foreground, with erythrocytes (EC) within them. A = alveolus; D = alveolar duct; PK = pore of Kohn; AR = alveolar entrance to duct; * = connective tissue fibers. The encircled asterisk is at a junction of 3 septa. The arrows indicate the edges of a type I alveolar epithelial cell. (Reproduced with permission from Fishman AP, Kaiser LR, Fishman JA, et al: *Pulmonary Diseases and Disorders*, 3rd ed. New York: McGraw-Hill; 1998.)

In Figure 1–4 the alveolar septum appears to be almost entirely composed of pulmonary capillaries.

Red blood cells (erythrocytes) can be seen inside the capillaries at the point of section.

Elastic and connective tissue fibers, not visible in the figure e, are found between the capillaries in the alveolar septa.

Also shown in these figures are the pores of Kohn or interalveolar communications.



Zone	Generation			Diameter, cm	Length, cm	Number	Total cross-sectional area, cm^2
Conducting zone	Trachea		0	1.80	12.0	1	2.54
	Bronchi		1	1.22	4.8	2	2.33
	↓		2	0.83	1.9	4	2.13
			3	0.56	0.8	8	2.00
	Bronchioles		4	0.45	1.3	16	2.48
	↓		5	0.35	1.07	32	3.11
	Terminal bronchioles		↓ 16	↓ 0.06	↓ 0.17	↓ 6×10^4	↓ 180.0
Transitional and respiratory zones	Respiratory bronchioles		17	↓	↓	↓	↓
			18				
			19	0.05	0.10	5×10^5	10^3
	Alveolar ducts	T_3	20	↓	↓	↓	↓
		T_2	21				
		T_1	22				
	Alveolar sacs	T	23	0.04	0.05	8×10^6	10^4

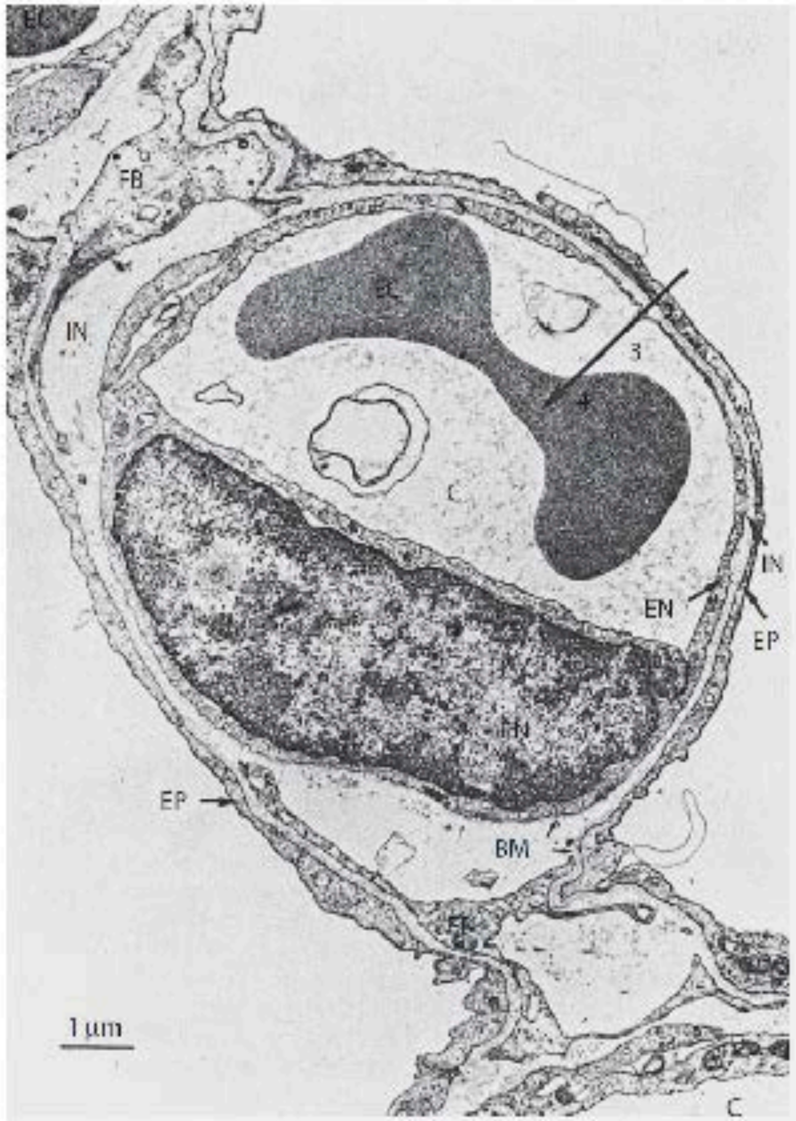


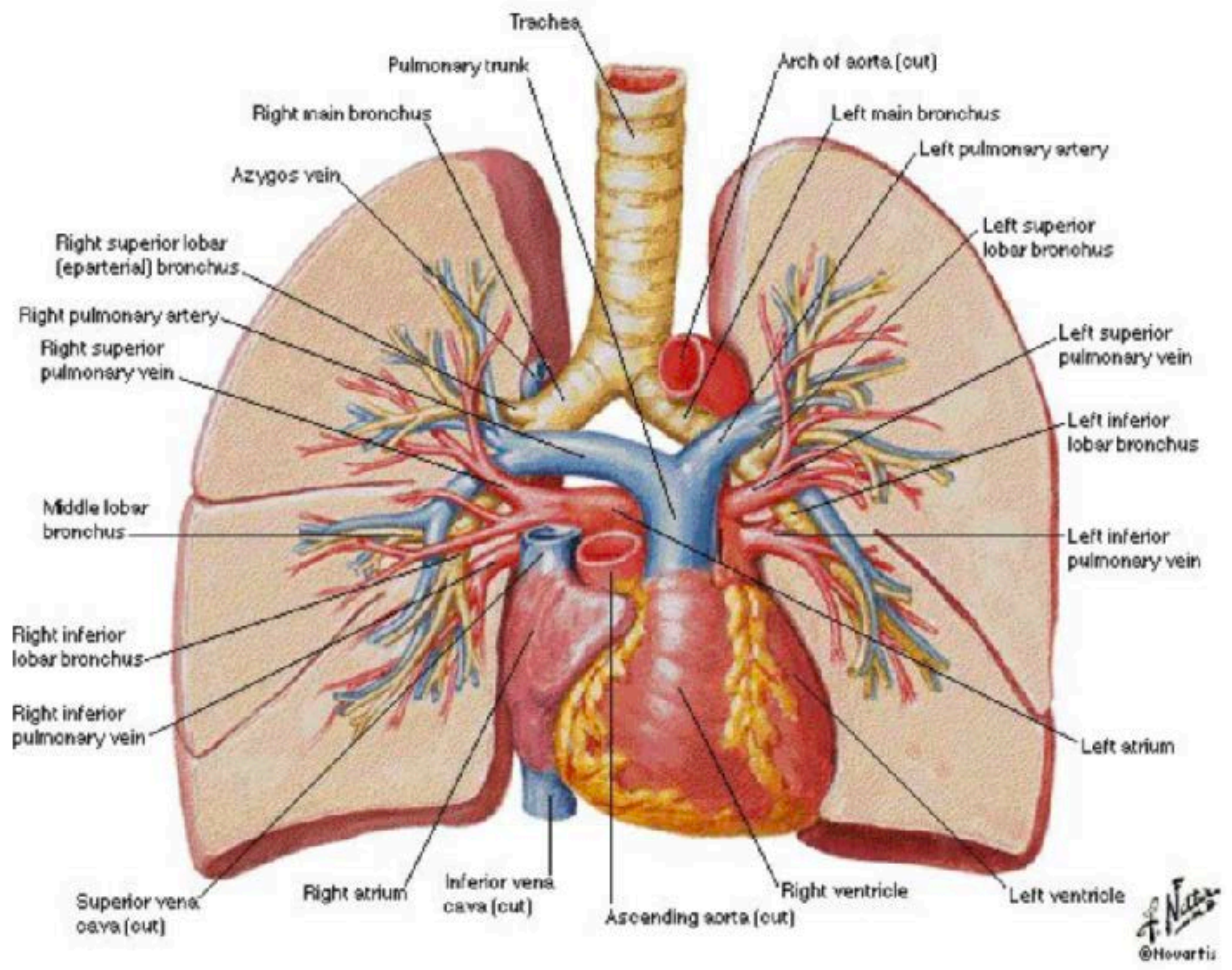
Figure 1–5. Transmission electron micrograph of a cross section of a pulmonary capillary. An erythrocyte (EC) is seen within the capillary. C = capillary; EN = capillary endothelial cell (note its large nucleus); EP = alveolar epithelial cell; IN = interstitial space; BM = basement membrane; FB = fibroblast processes; 2, 3, 4 = diffusion pathway through the alveolar-capillary barrier, the plasma, and the erythrocyte, respectively. Note that the alveolar-capillary barrier appears to have a thin side and a thick side that has a greater interstitial space and more connective tissue. (Reproduced with permission from Weibel ER. Morphometric estimation of pulmonary diffusion capacity, I. Model and method. *Respir Physiol.* 1970;11:54–75.)

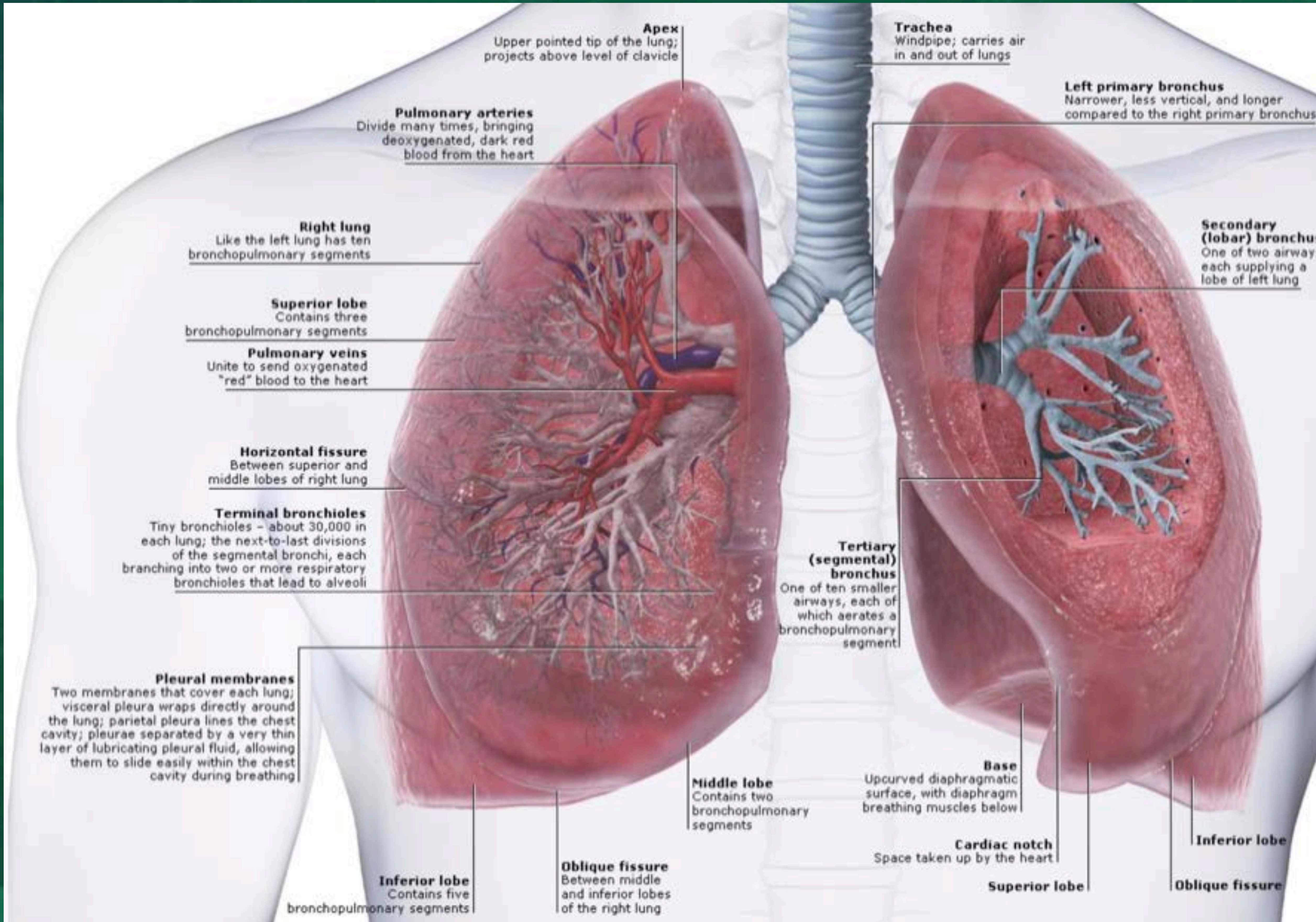
The barrier to gas exchange between the alveoli and pulmonary capillaries can also be seen in Figure 1–5.

It consists of the alveolar epithelium, the capillary endothelium, and the interstitial space between them. Gases must also pass through the fluid lining the alveolar surface (not visible in Figure 1–5) and the plasma in the capillary.

The barrier to diffusion is normally 0.2- to 0.5-µm thick.

Pulmonary Arteries and Veins




Apex
Upper pointed tip of the lung; projects above level of clavicle
Trachea
Windpipe; carries air in and out of lungs
Pulmonary arteries
Divide many times, bringing deoxygenated, dark red blood from the heart
Left primary bronchus
Narrower, less vertical, and longer compared to the right primary bronchus
Right lung
Like the left lung has ten bronchopulmonary segments
Secondary (lobar) bronchus
One of two airways, each supplying a lobe of left lung
Superior lobe
Contains three bronchopulmonary segments
Pulmonary veins
Unite to send oxygenated "red" blood to the heart
Horizontal fissure
Between superior and middle lobes of right lung
Terminal bronchioles
Tiny bronchioles – about 30,000 in each lung; the next-to-last divisions of the segmental bronchi, each branching into two or more respiratory bronchioles that lead to alveoli
Tertiary (segmental) bronchus
One of ten smaller airways, each of which aerates a bronchopulmonary segment
Pleural membranes
Two membranes that cover each lung; visceral pleura wraps directly around the lung; parietal pleura lines the chest cavity; pleurae separated by a very thin layer of lubricating pleural fluid, allowing them to slide easily within the chest cavity during breathing
Middle lobe
Contains two bronchopulmonary segments
Base
Upcurved diaphragmatic surface, with diaphragm breathing muscles below
Cardiac notch
Space taken up by the heart
Inferior lobe
Oblique fissure
Between middle and inferior lobes of the right lung
Inferior lobe
Contains five bronchopulmonary segments
Superior lobe
Oblique fissure

We shall not cease from exploration

And the end of all our exploring

Will be to arrive where we started

And know the place for the first time.

T.S. Eliot --- "Little Gidding" ... *Four Quartets*

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