# INTIMATE STRANGERS:
## MICROBIAL PARTNERS IN THE NATURAL WORLD

OLLI

SPRING 2020

# A VERY BRIEF COURSE SYLLABUS

- THE MICROBIAL BIOSPHERE: THE BIRTH OF MICROBIOLOGY, A LITTLE HISTORY, A MICROBIAL CENSUS OF THE WORLD
- MICROBIAL EVOLUTION: HOW MICROBES SHAPED THE PHYSICAL WORLD. EVOLUTION OF HIGHER ORGANISMS. MICROBES AS COMMUNITY BUILDERS
- MICROBIAL CHEMISTRIES AND PHYSIOLOGIES: MICROBES IN NUTRIENT CYCLES AND FOOD WEBS
- MICROBES AND OTHER ORGANISMS: TALES OF COEXISTENCE.
- MICROBES AND INSECTS: INTIMATE RELATIONS AND LIVING STRATEGIES
- HUMAN MICROBIOME. FROM MOTHERS TO PROGENY
- BAD MICROBES: PATHOGENS AND MECHANISMS OF PATHOGENESIS
- BAD MICROBES: PATHOGEN-HOST INTERACTIONS. FUTURE TRENDS

# LECTURE 1:

# THE MICROBIAL BIOSPHERE

DISCOVERY OF MICROBES

19TH CENTURY: MICROBES AND DISEASE

THE MOLECULAR BIOLOGY REVOLUTION: MICROBIOLOGY COMES OF AGE

MICROBES EVERYWHERE!

IMPLICATIONS FOR ORIGIN OF LIFE

IMPLICATIONS FOR SPACE EXPLORATION

IGUAZU

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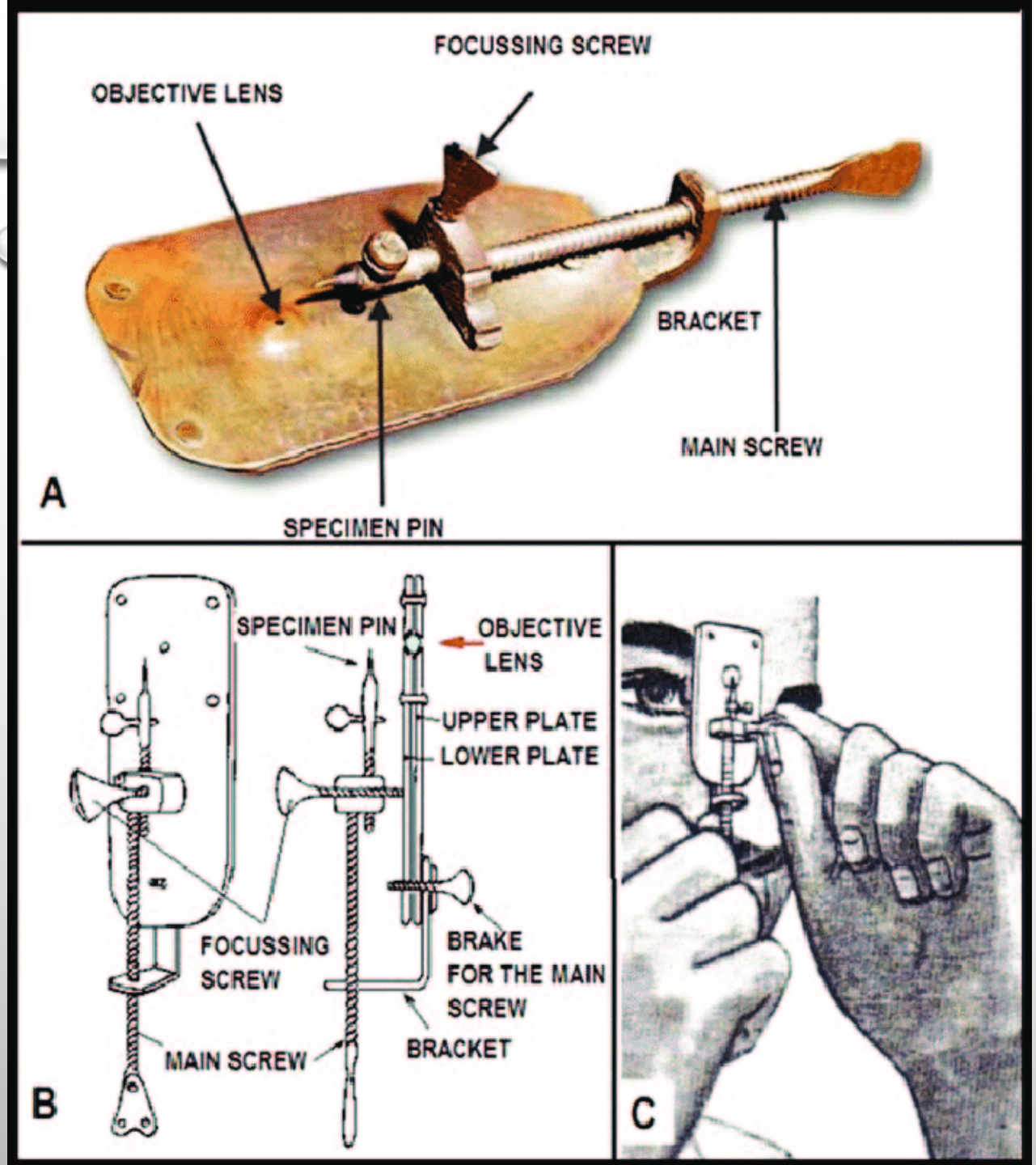
Anton Leeuwenhoek - circa 1670


FOCUSSING SCREW
OBJECTIVE LENS
BRACKET
MAIN SCREW
SPECIMEN PIN
A
SPECIMEN PIN
OBJECTIVE LENS
UPPER PLATE
LOWER PLATE
FOCUSSING SCREW
BRAKE FOR THE MAIN SCREW
BRACKET
MAIN SCREW
B
C

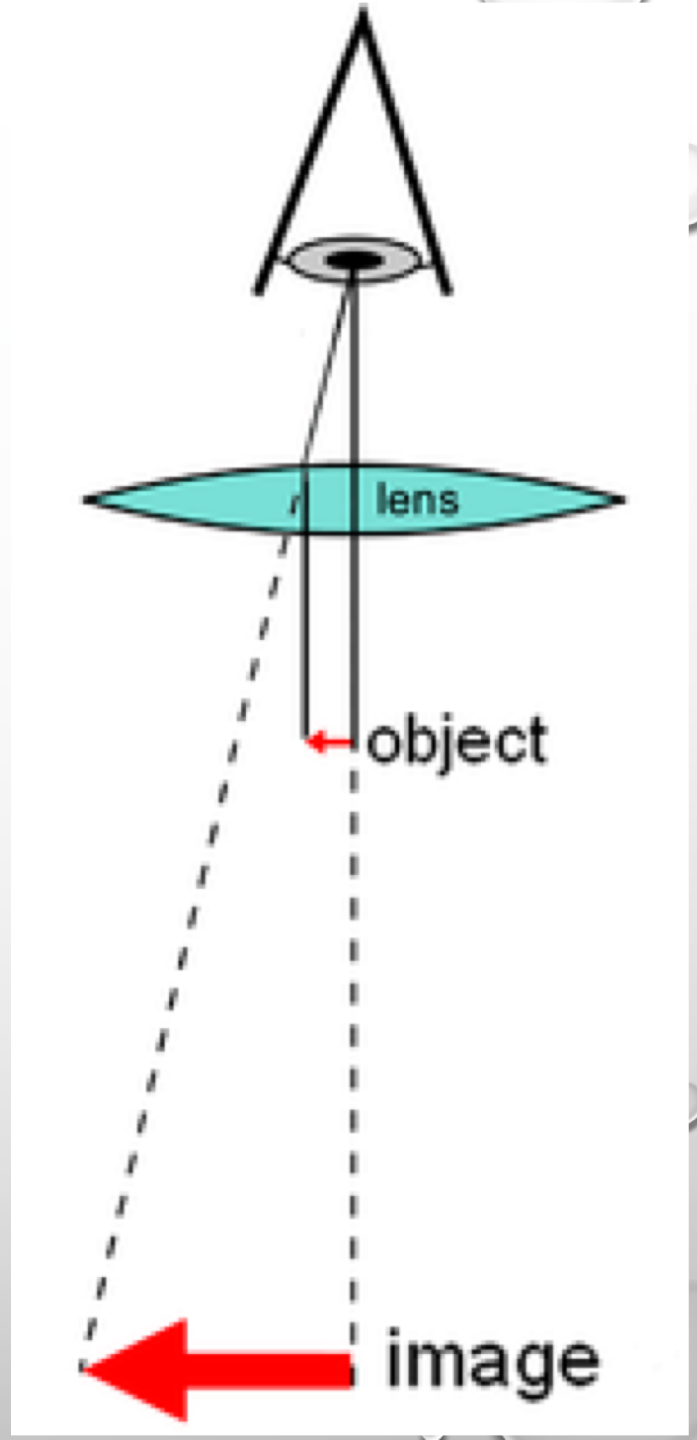

lens
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Fig: 1.

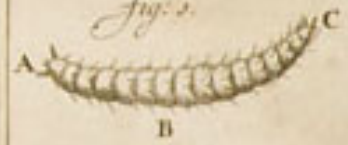



Fig: 2.

Fig: 3.

Fig: 4.

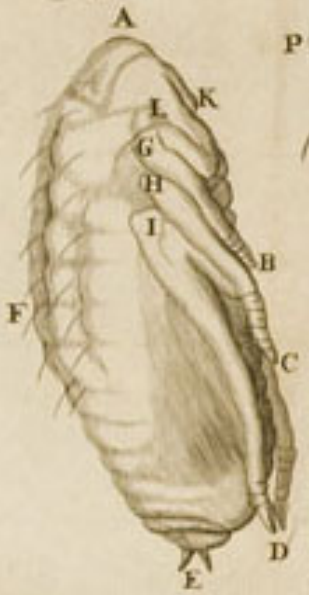



Fig: 5.

Fig: 6.

Fig: 18.




Fig: 21.

Fig: 7.

Fig: 8.

Fig: 9.

Fig: 10.

Fig: 19.

Fig: 17.

Fig: 12.

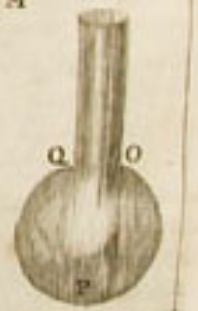
Fig: 13.

Fig: 14.

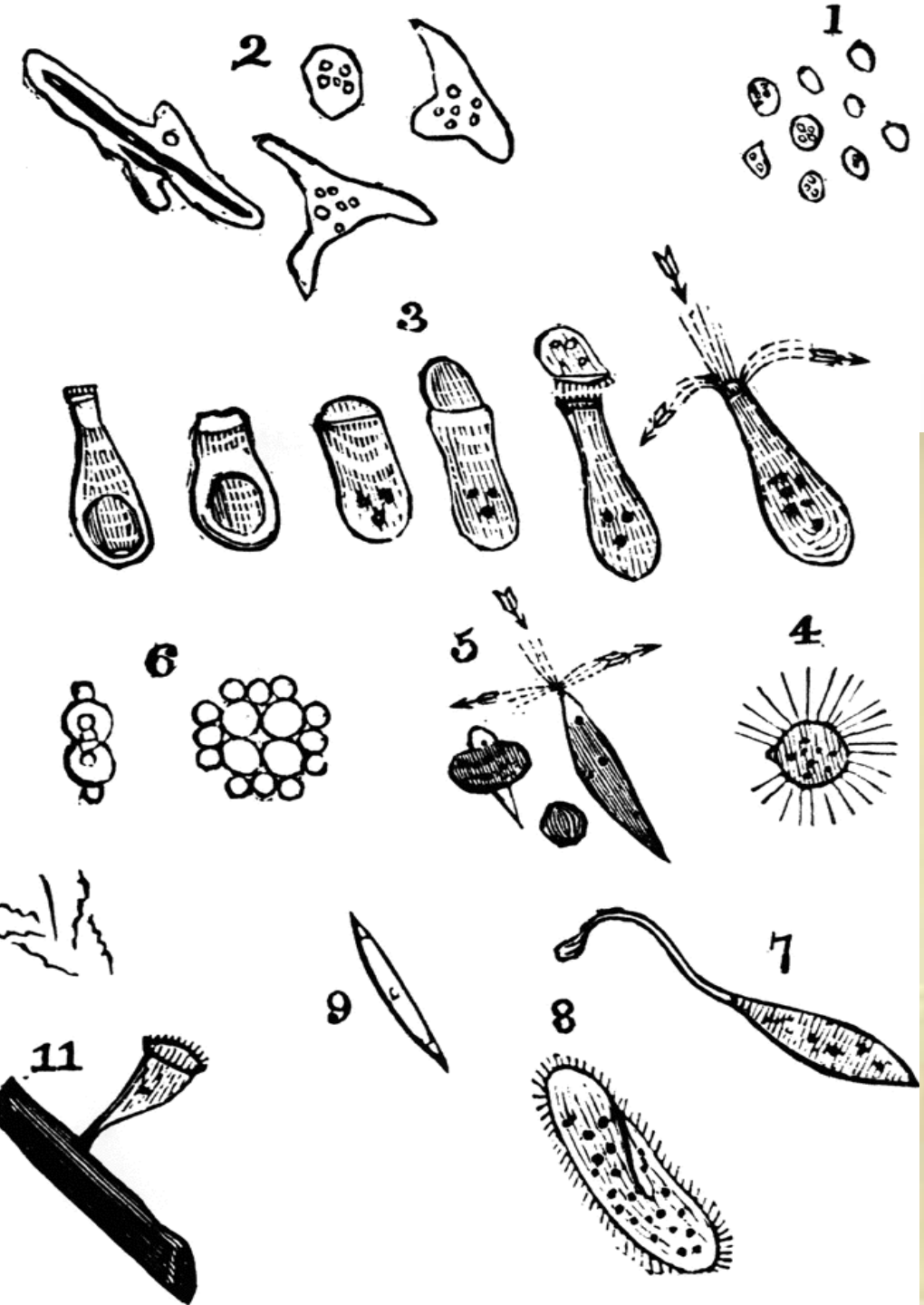
Fig: 15.

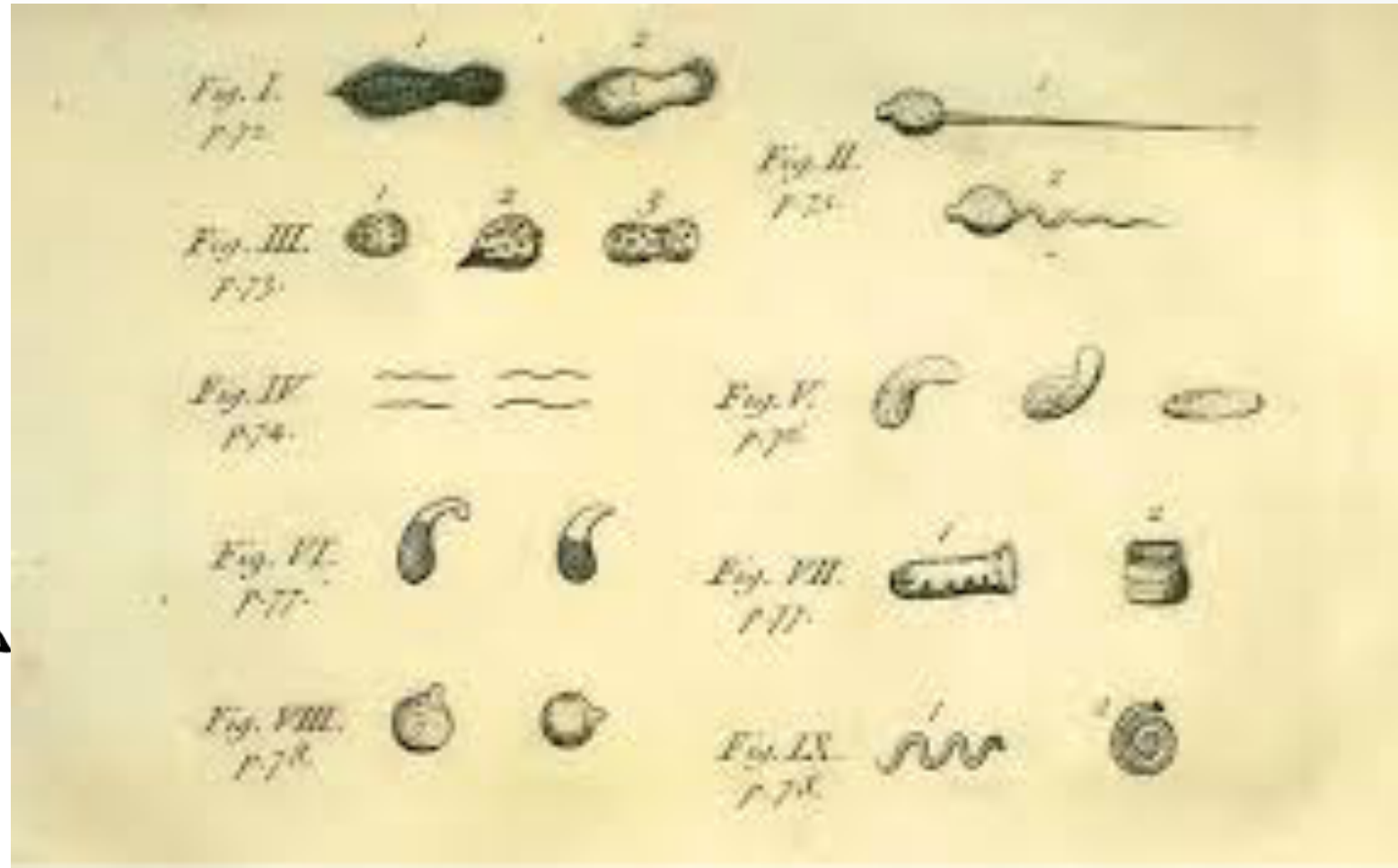
Fig: 16.

Fig: 20.



# Leeuwenhoek's Animalcules



# Robert Hooke (1635-1703)

(Published 1665)

MICROGRAPHIA:

OR SOME

*Physiological Descriptions*

OF

MINUTE BODIES

MADE BY

MAGNIFYING GLASSES.

WITH

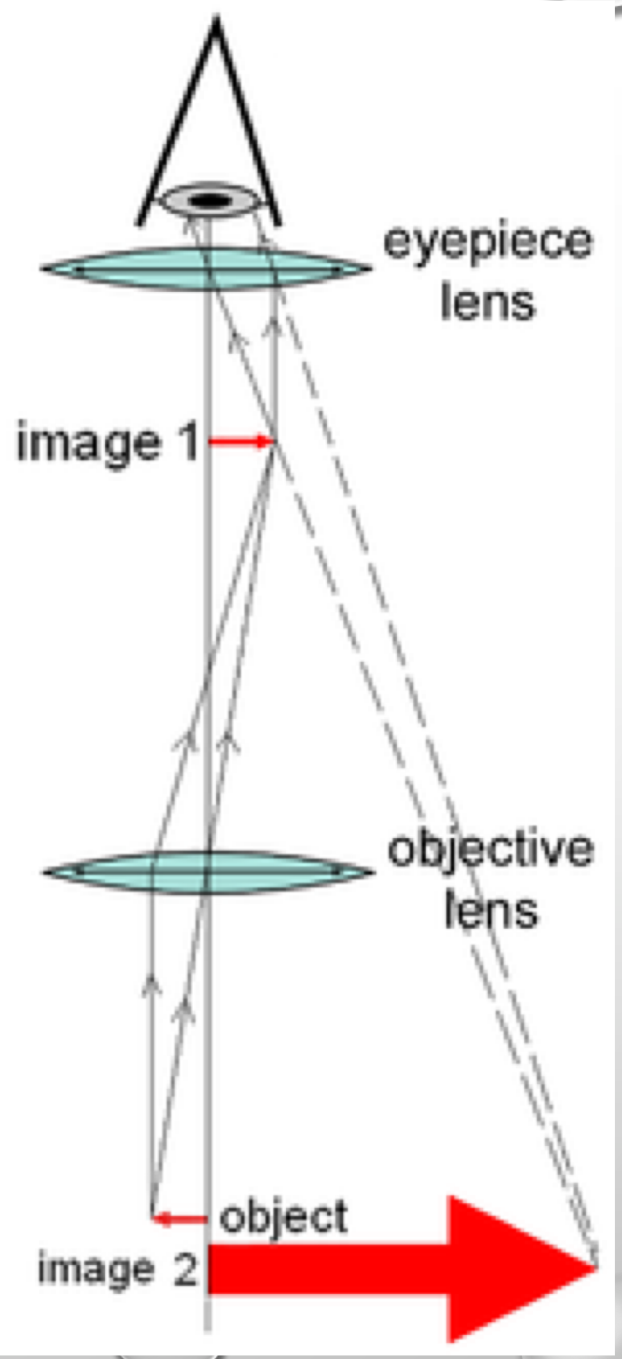
OBSERVATIONS and INQUIRIES thereupon.

By *R. HOOKE*, Fellow of the ROYAL SOCIETY.

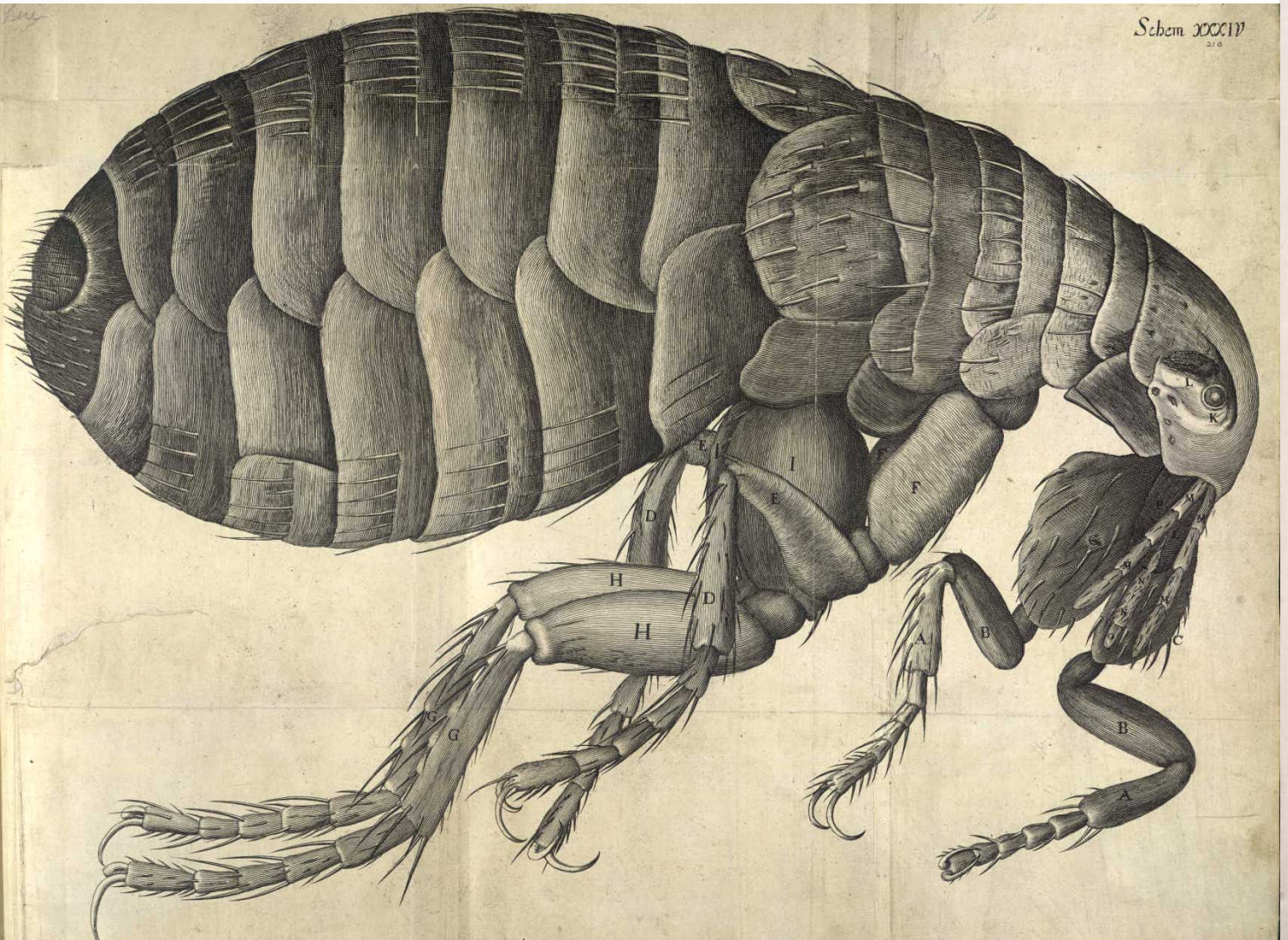
*Non possis oculo quantum contendere Linceus,*
*Non tamen idcirco contemnas Lippus inungi.* Horat. Ep. lib. 1.

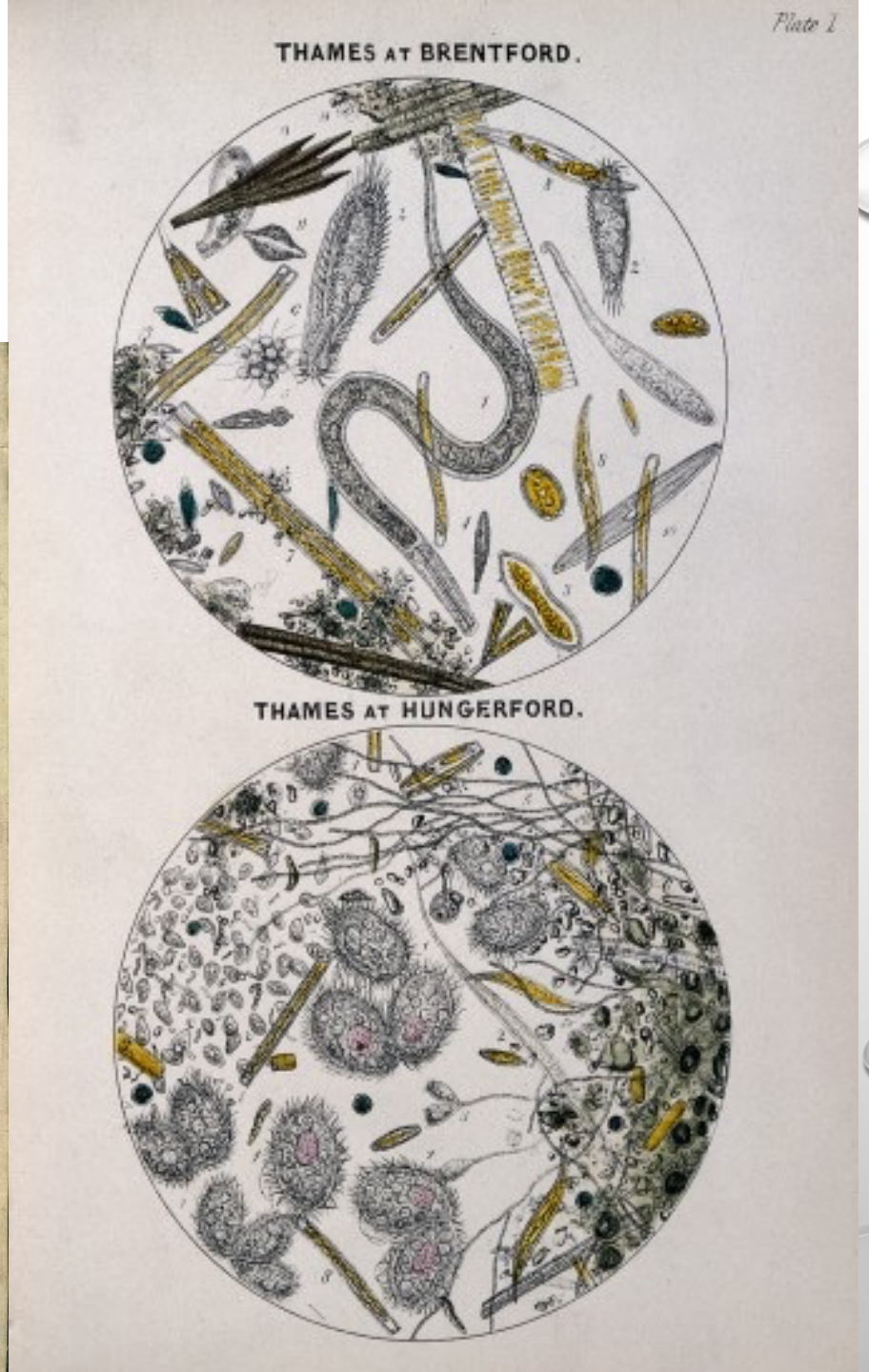
NVLLIVS IN VERBA

*LONDON*, Printed by *Jo. Martyn*, and *Ja. Allestry*, Printers to the ROYAL SOCIETY, and are to be sold at their Shop at the *Bell* in S. *Paul's* Church-yard. M DC LX V.


eyepiece lens
image 1
objective lens
object
image 2

# Hooke's Drawings



# MICROSCOPY COMES OF AGE

## CARL ZEISS (1816-1888)

Circa 1879

# PRESSING SCIENTIFIC QUESTIONS IN THE 1800'S

- DOES SPONTANEOUS GENERATION OCCUR?

- WHAT IS THE NATURE OF INFECTIOUS DISEASES?

# LOUIS PASTEUR (1822-1895)

- PRINCIPLES OF VACCINATION: CREATED FIRST VACCINES AGAINST ANTHRAX AND RABIES
- FERMENTATION (YEAST WAS RESPONSIBLE FOR FERMENTATION TO PRODUCE ALCOHOL FROM SUGAR IN WINE)
- WHEN A DIFFERENT MICROORGANISM CONTAMINATED THE WINE, LACTIC ACID WAS PRODUCED, MAKING THE WINE SOUR
- PASTEURIZATION (HEATING TO A TEMPERATURE BETWEEN 60 AND 100 °C KILLED MOST MICROORGANISMS THUS DELAYING SPOILAGE)
- ALSO AN ACCOMPLISHED CHEMIST

# Pasteur's Test of Spontaneous Generation

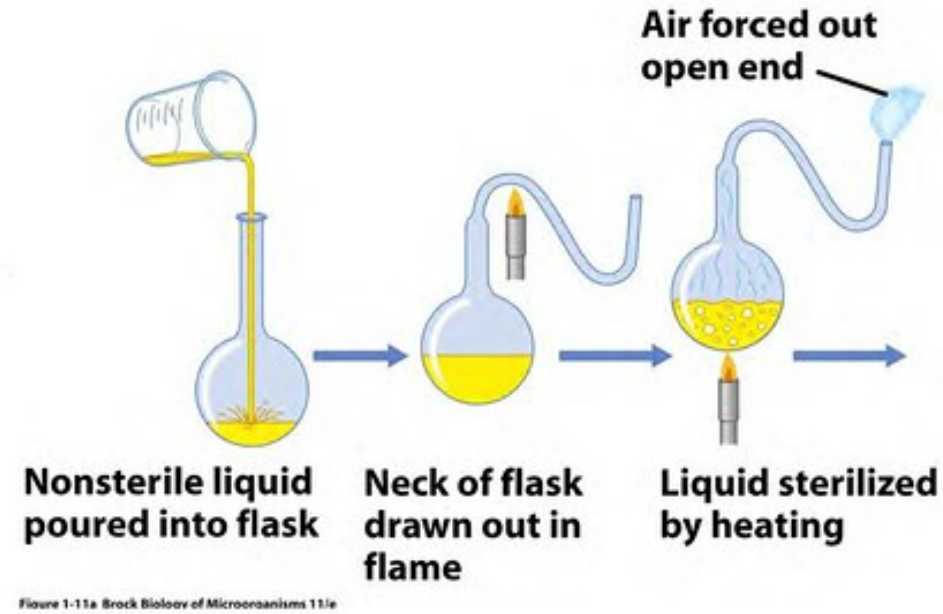



Figure 1-11a Brock Biology of Microorganisms 11/e

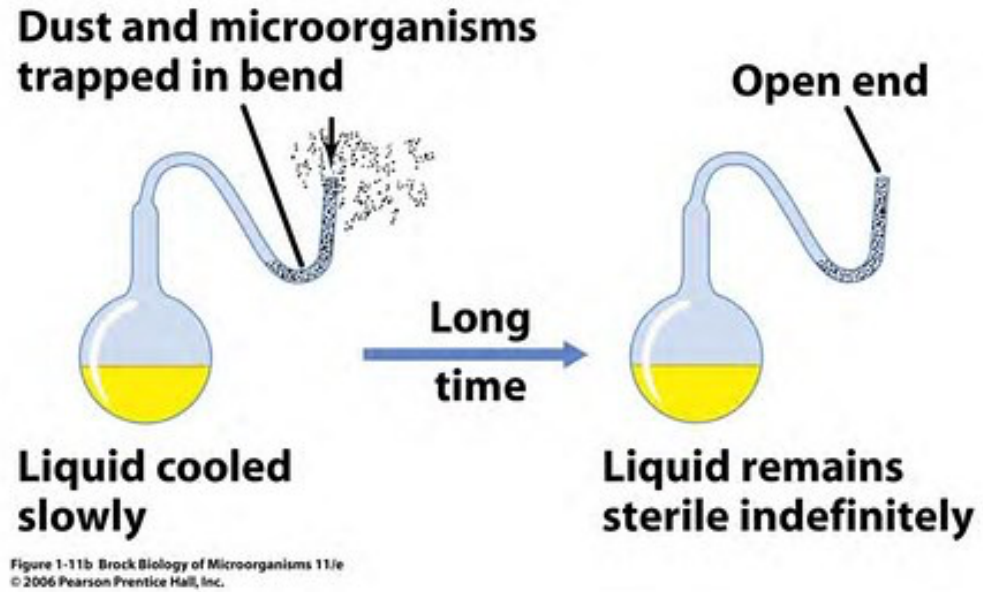



Figure 1-11b Brock Biology of Microorganisms 11/e
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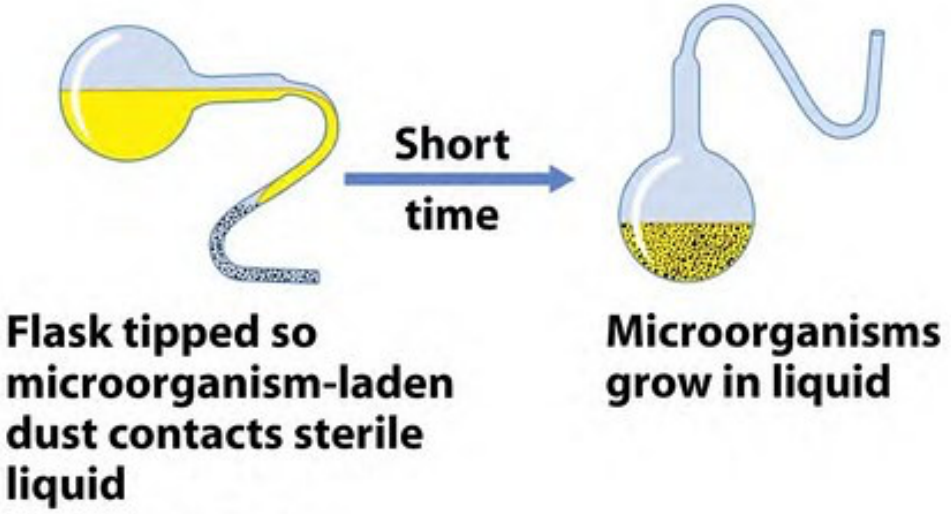


- BEYOND THE DEBUNKING OF SPONTANEOUS GENERATION OF LIFE FORMS, PASTEUR'S EXPERIMENTS DEMONSTRATED THAT:

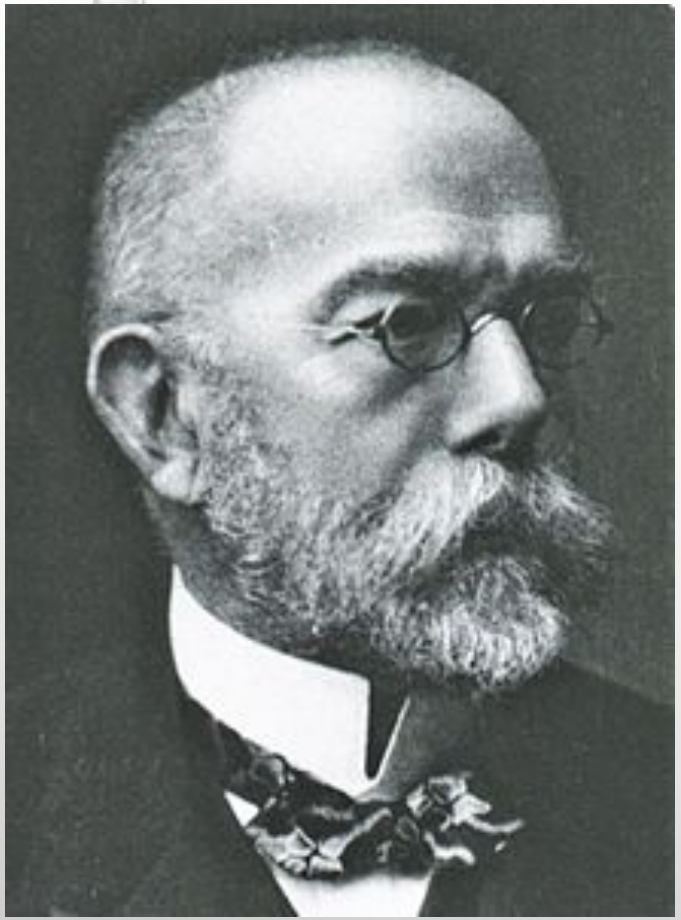
- THE PRESENCE AND ACTIVITIES OF MICROBES WERE RESPONSIBLE FOR FOOD SOURING

- THIS LED TO EFFECTIVE STERILIZATION TECHNIQUES, FIRST IMPLEMENTED BY JOSEPH LISTER, AN ENGLISH SURGEON

- BUT: "IF BACTERIA CAN MAKE DAIRY, FOOD AND WINE "ILL", THEN SHOULD IT NOT STAND TO REASON THAT THEY CAN DO THE SAME TO PEOPLE?"

- PROVIDED SUPPORT FOR THE GERM THEORY OF DISEASE

# ROBERT KOCH (1843-1910)



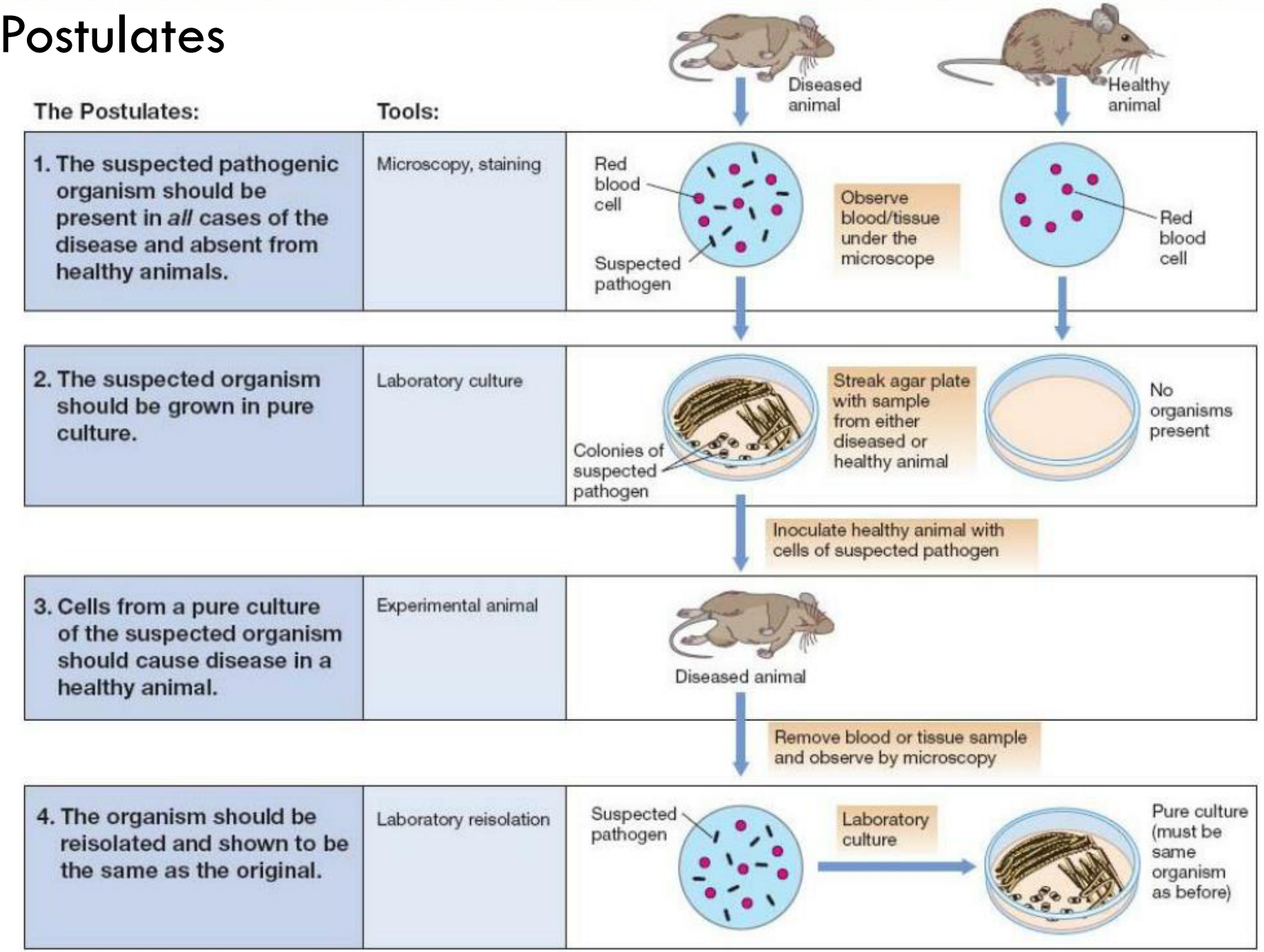
Robert Koch (1843-1910)

- **GERM THEORY OF DISEASE:** INFECTIOUS DISEASES ARE CAUSED BY MICROBIAL AGENTS

- IDENTIFIED CAUSATIVE AGENTS OF:
  - TUBERCULOSIS (MYCOBACTERIUM TUBERCULOSIS)
  - CHOLERA (VIBRIO CHOLERAE)
  - ANTHRAX (BACILLUS ANTHRACIS)

- NOBEL PRIZE IN PHYSIOLOGY AND MEDICINE IN 1905

# Koch's Postulates




Source: Madigan, Martinko, Dunlap and Clark, p. 15 (2009).

# LIMITATIONS OF KOCH'S POSTULATES

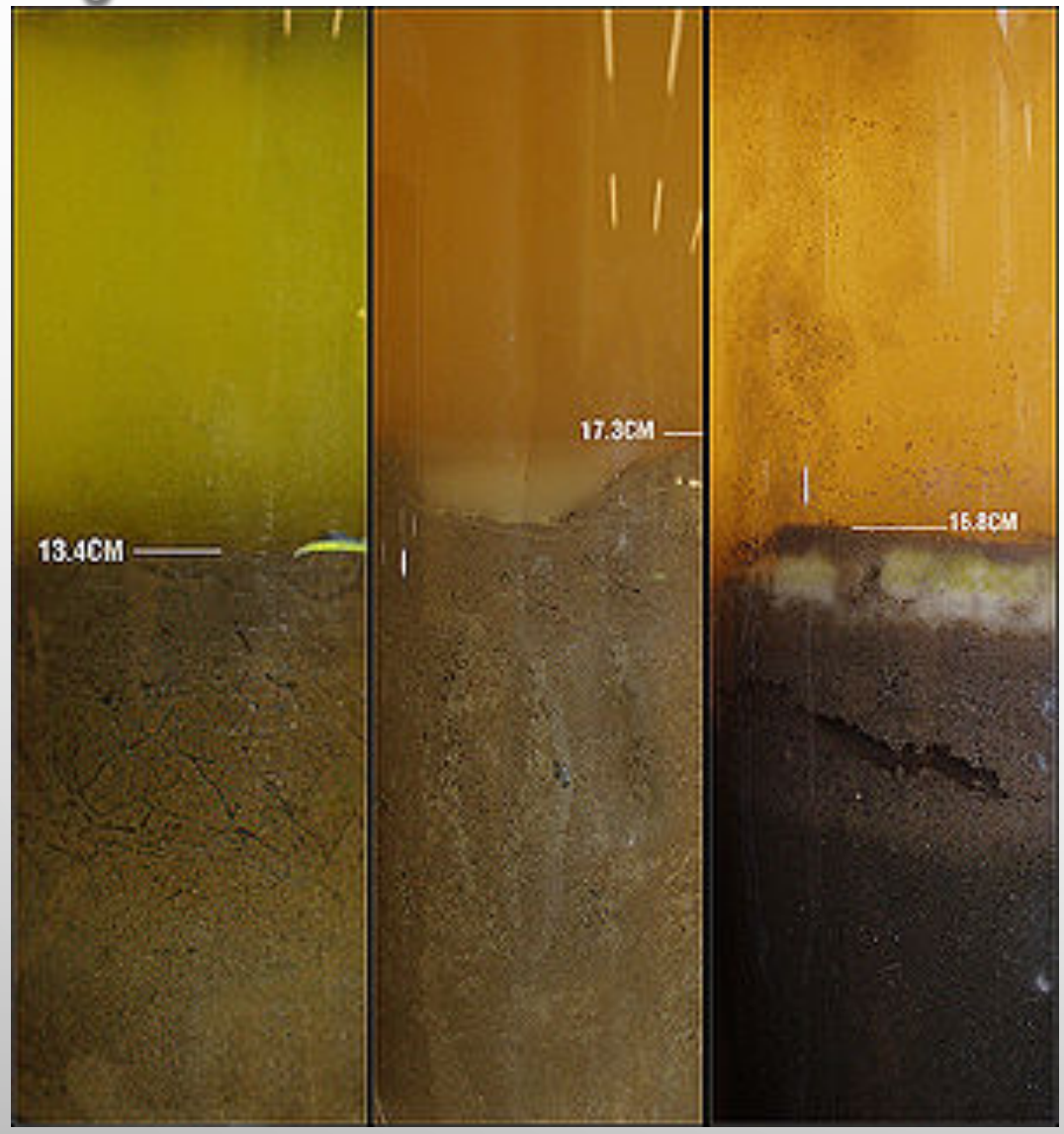
- DIFFICULT TO ISOLATE THE PATHOGEN IN PURE CULTURE
- SOME DISEASE-CAUSING AGENTS MAY ALSO BE FOUND IN HEALTHY INDIVIDUALS (E.G. CHOLERA)
- EVEN IF A PATHOGEN IS PRESENT, THE COMMUNITY OF MICROBES MAY BE RESPONSIBLE FOR KEEPING THE PATHOGEN IN CHECK, THUS NOT CAUSING DISEASE
- DO NOT ACCOUNT FOR VIRAL DISEASES (MANY VIRUSES DO NOT CAUSE ILLNESS IN ALL INFECTED INDIVIDUALS, A REQUIREMENT OF THE FIRST POSTULATE)
- TO BE FAIR, VIRUSES HAD NOT YET BEEN DISCOVERED

- BUT IT JUMP-STARTED THE SCIENCE OF MICROBIOLOGY!

# SERGEI WINOGRADSKY (1856-1953)

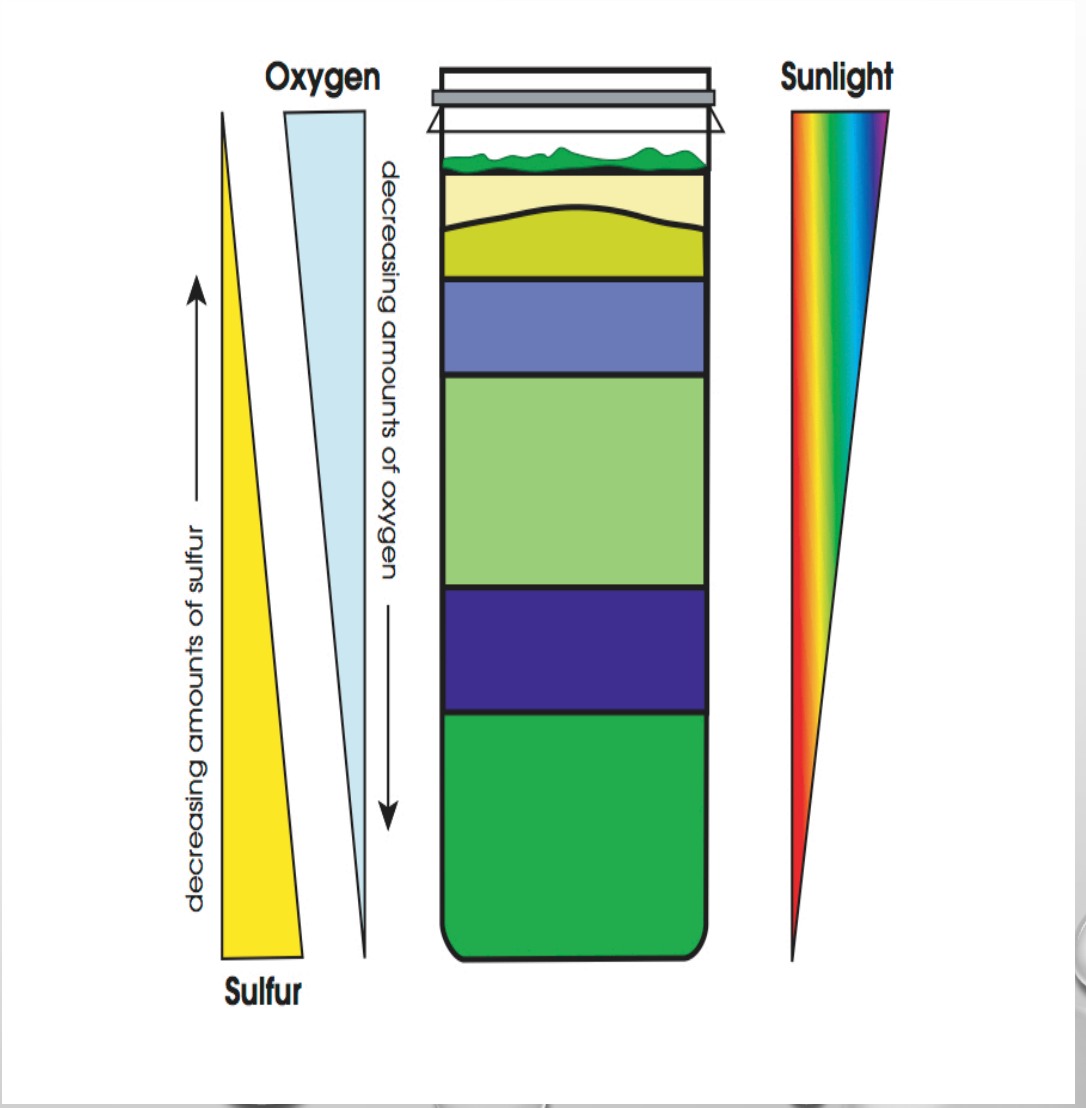
- RUSSIAN, BORN IN KIEV
- SOIL MICROBIOLOGIST
- MICROBIOLOGY **NOT** IN THE CONTEXT OF MEDICAL SCIENCE
- PIONEERED THE CYCLE-OF-LIFE CONCEPT
- FIRST TO DEMONSTRATE THAT MICROBES CAN EXTRACT ENERGY FROM INORGANIC COMPOUNDS
- LAID THE FOUNDATIONS FOR MICROBIAL ECOLOGY

# WINOGRADSKY'S COLUMN



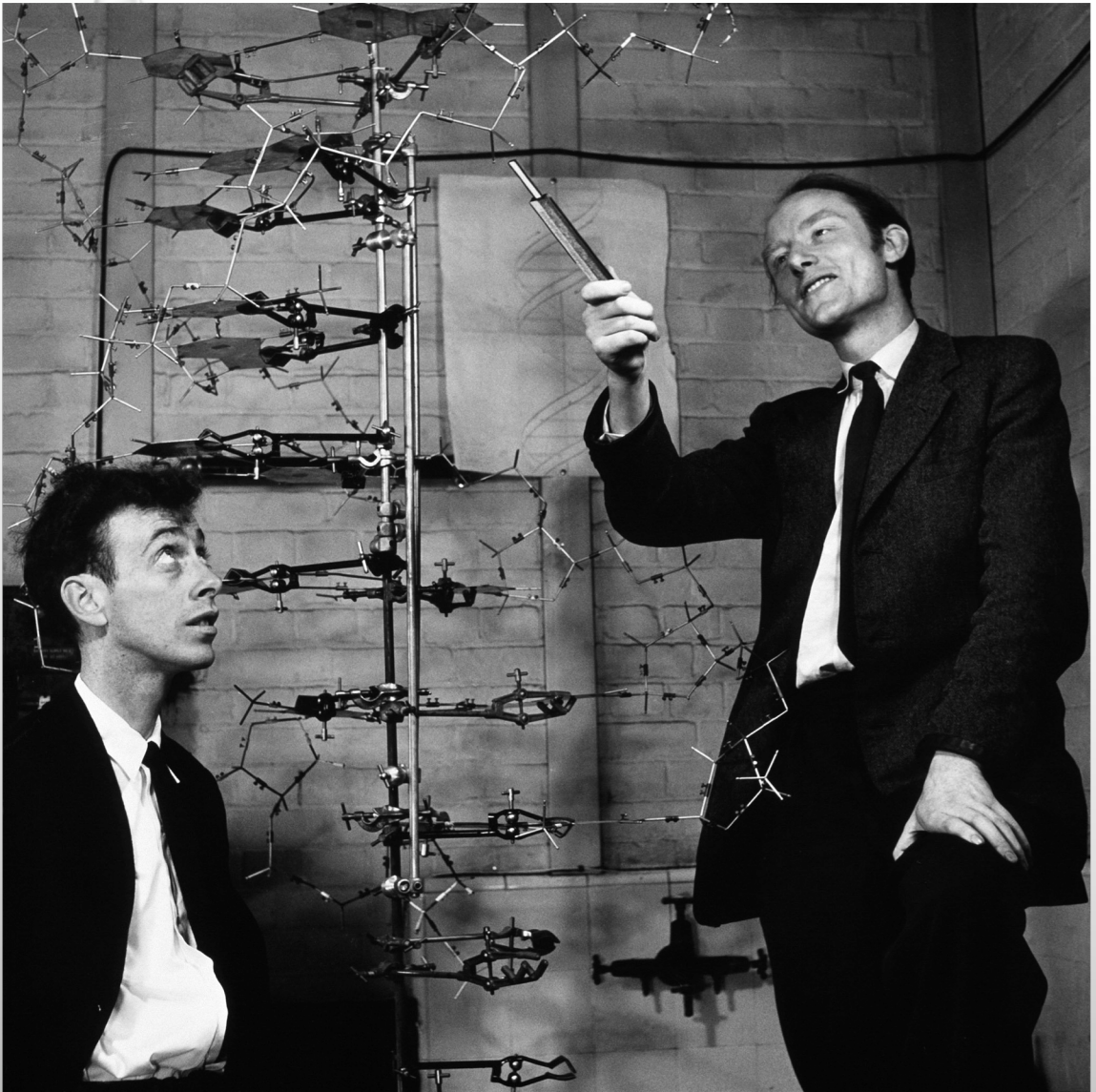

- SIMPLE DEVICE FOR CULTURING A LARGE DIVERSITY OF MICROBES
- A TALL GLASS (30 CM LONG, >5 CM WIDE) IS FILLED ONE THIRD FULL OF POND MUD
- SUPPLEMENT WITH CELLULOSE, A SOURCE OF PHOSPHATE, NITRATE, SULFUR AND OXYGEN ADDITIVES
- SEAL
- INCUBATE SEVERAL MONTHS IN NATURAL LIGHT

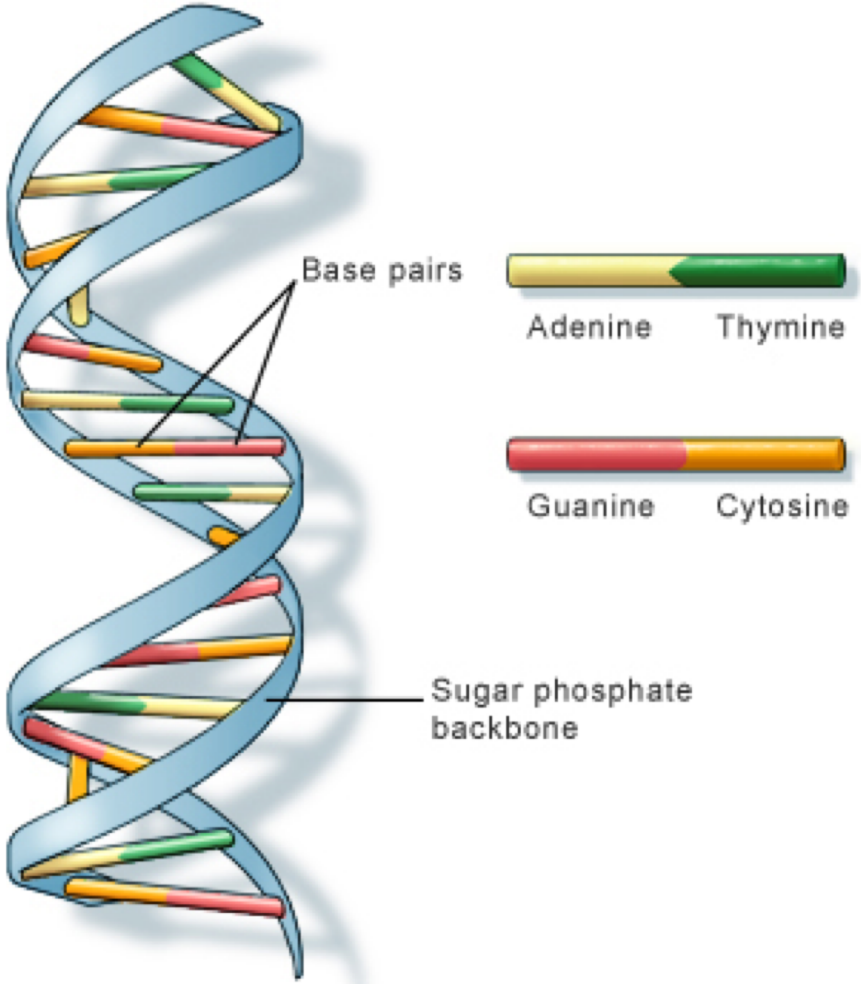
# THEN MUCK HAPPENS…



# MICROBIOLOGY COMES OF AGE — THE MOLECULAR REVOLUTION

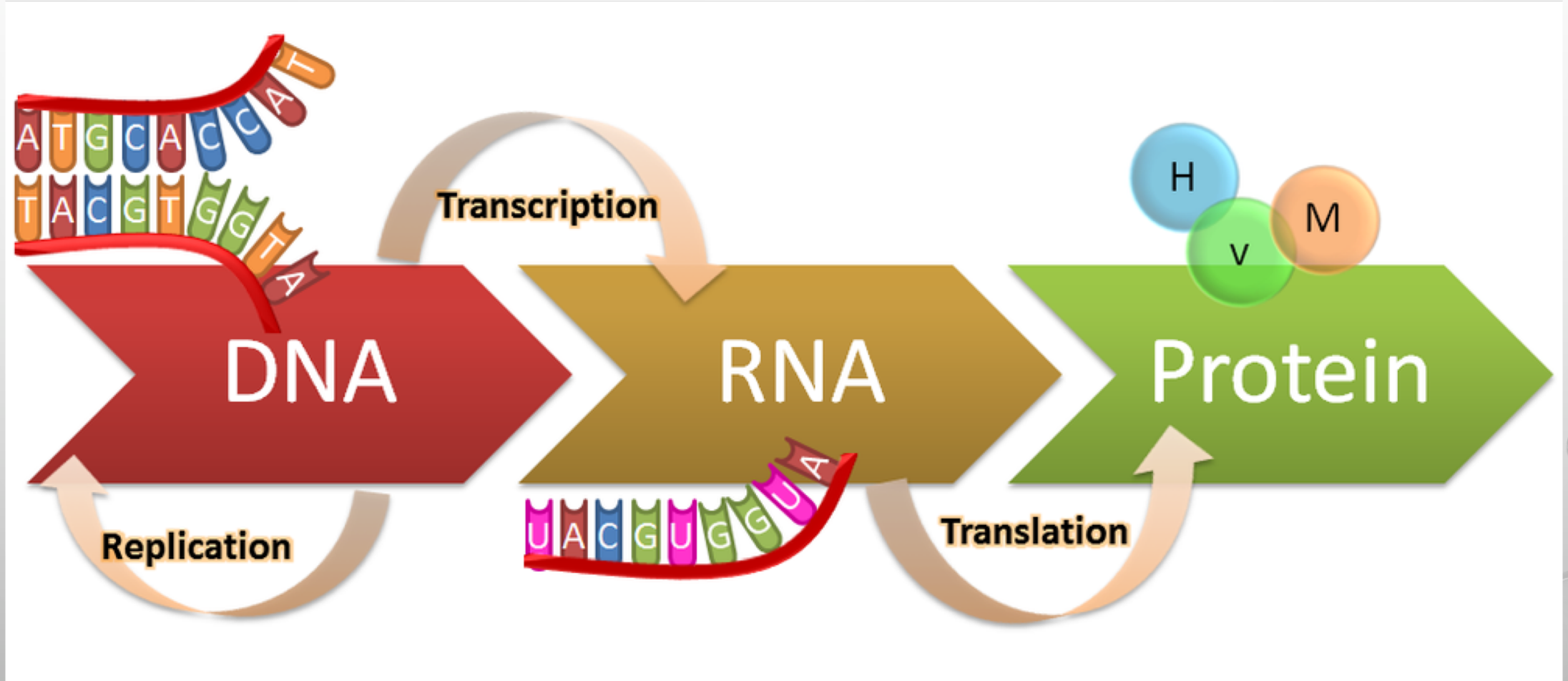
## THE STRUCTURE OF DNA – WATSON AND CRICK – 1953






U.S. National Library of Medicine

# THE FLOW OF GENETIC INFORMATION – BIOLOGY'S CENTRAL DOGMA



# CRICK'S MOMENTOUS INSIGHT (1957): **PROTEINS** *(…AND OTHER MACROMOLECULES…)* **ARE REPOSITORIES OF EVOLUTIONARY HISTORY**

…"biologists should realize that before long we shall have a subject which might be called 'protein taxonomy' – the study of the amino acid sequences of the proteins of an organism and the comparison of them between species"

Therefore, molecular markers can and do define organisms, much as anatomical traits do

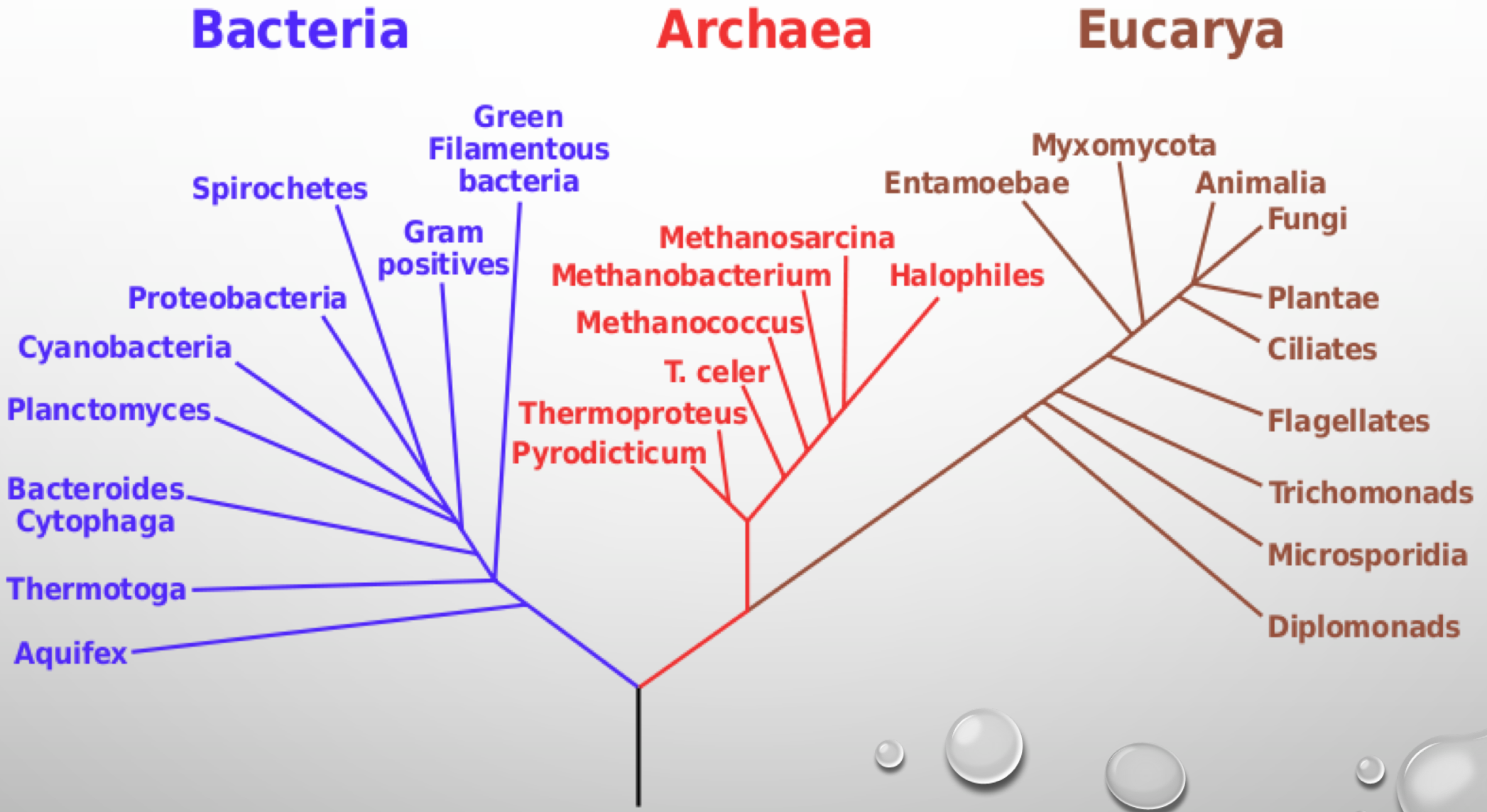
# CLASSIFICATION GOES MOLECULAR

SET OUT TO CLASSIFY MICROBES ON THE BASIS OF MOLECULAR SEQUENCE DATA

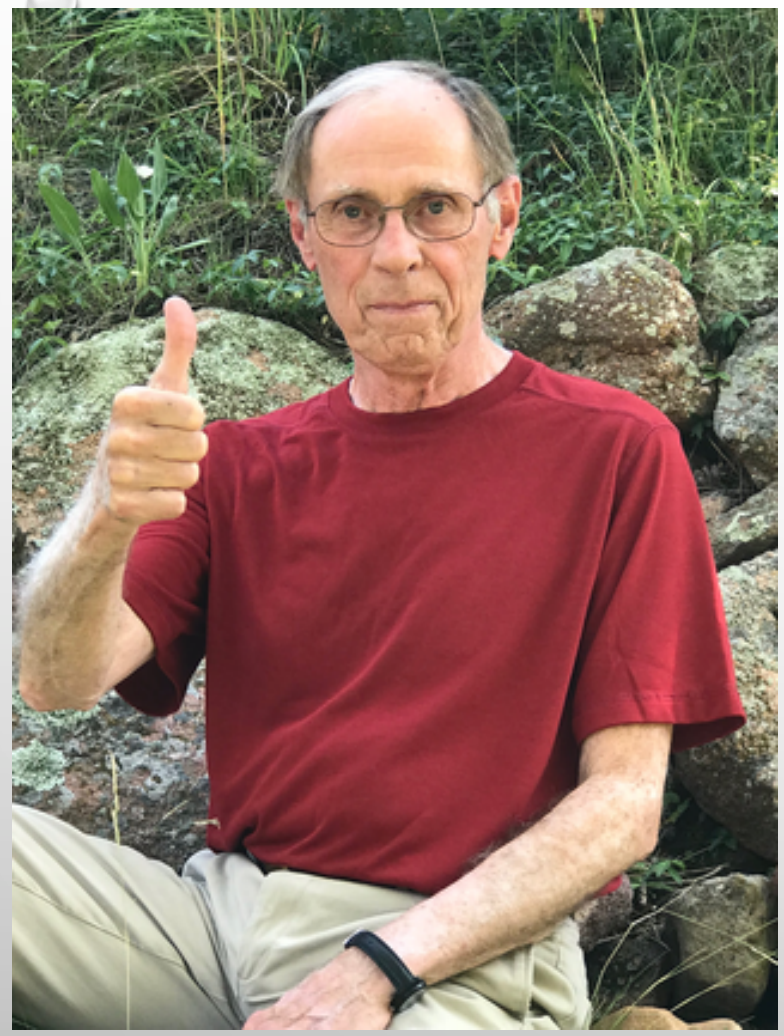
- STILL RELIANT ON PURE CULTURES OF ORGANISMS TO GET THE MOLECULAR SEQUENCES

Carl Woese (1928-2012) - Department of Microbiology, UIUC

# Phylogenetic Tree of Life



# THE PHYLOGENETIC TREE AS FRAMEWORK



Norman Pace (1942-)

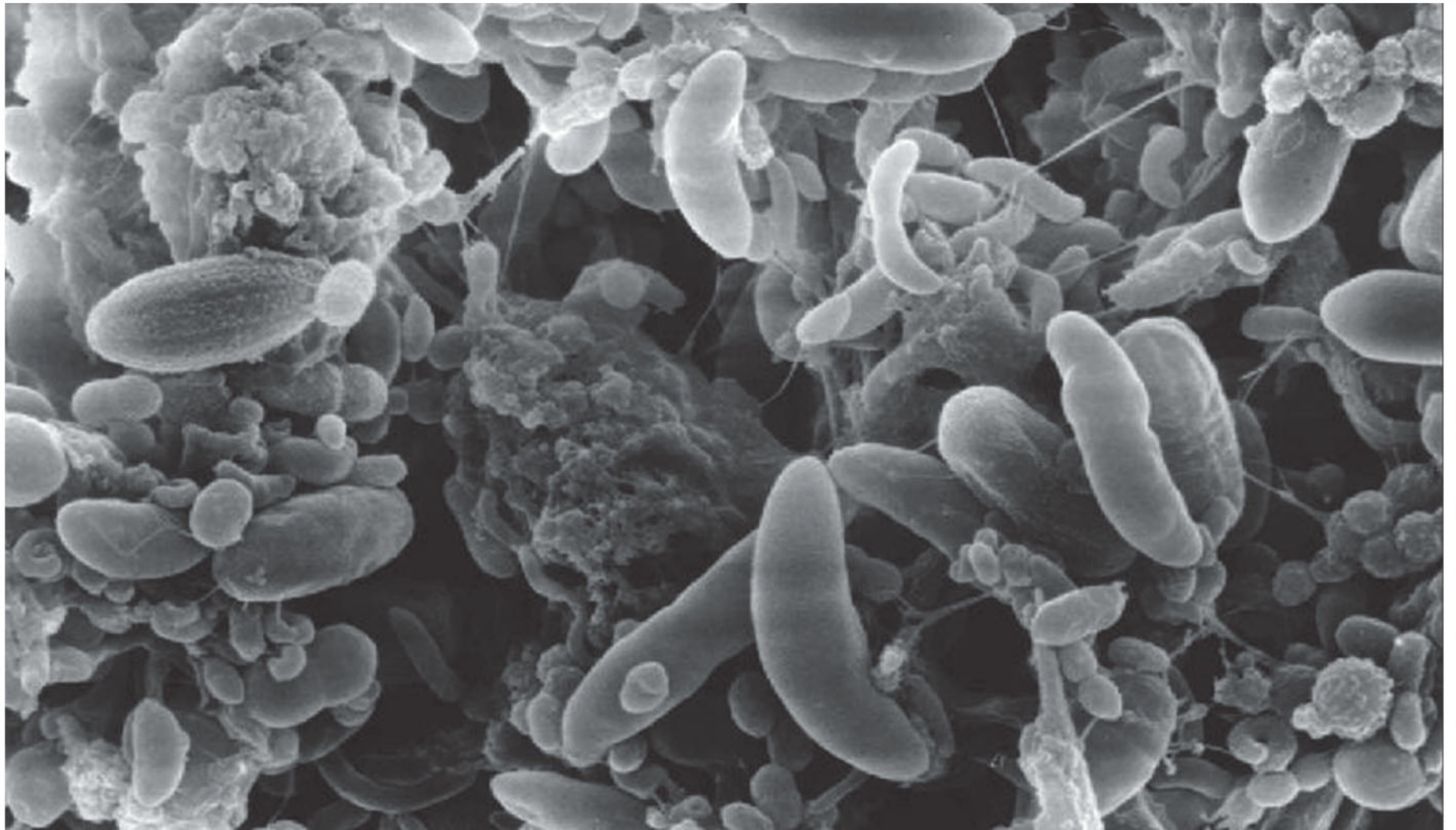
- SINCE ONLY A SMALL FRACTION OF MICROBES ARE AMENABLE TO BE CULTURED *IN VITRO*, HOW MUCH OF THE TREE OF LIFE ARE WE MISSING?
- **WHO'S THERE?**
- GIVEN THE FRAMEWORK, ANY SEQUENCE (NOT ONLY THE ORGANISM THAT CONTAINS IT) CAN NOW BE MAPPED ONTO THE UNIVERSAL TREE
- THE RE-BIRTH OF MICROBIAL ECOLOGY (INCLUDING THE HUMAN MICROBIOME)

# IMPACT OF MICROORGANISMS ON HUMANS

- AGENTS OF DISEASE
- HUMAN HEALTH
- HUMAN NUTRITION
- AGRICULTURE
- FOOD PRODUCTION
- ENERGY
- INDUSTRY
- ENVIRONMENT
- AND THEY ARE EVERYWHERE…

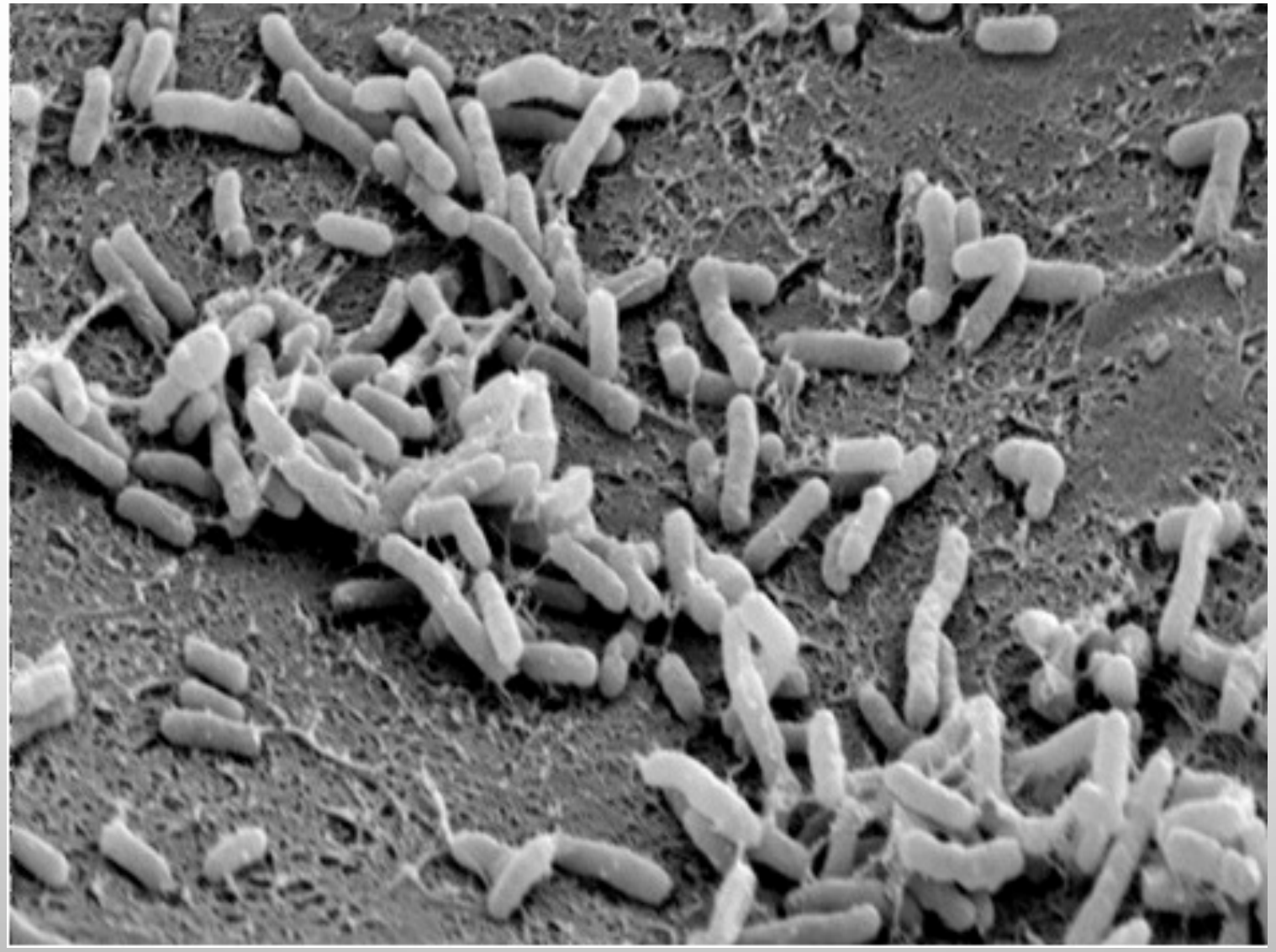
# ON THE SURFACE OF LEAVES

# IN THE DIGESTIVE SYSTEM OF ANIMALS



UNIV., FACULTY OF BIORESOURCES

# IN SOIL

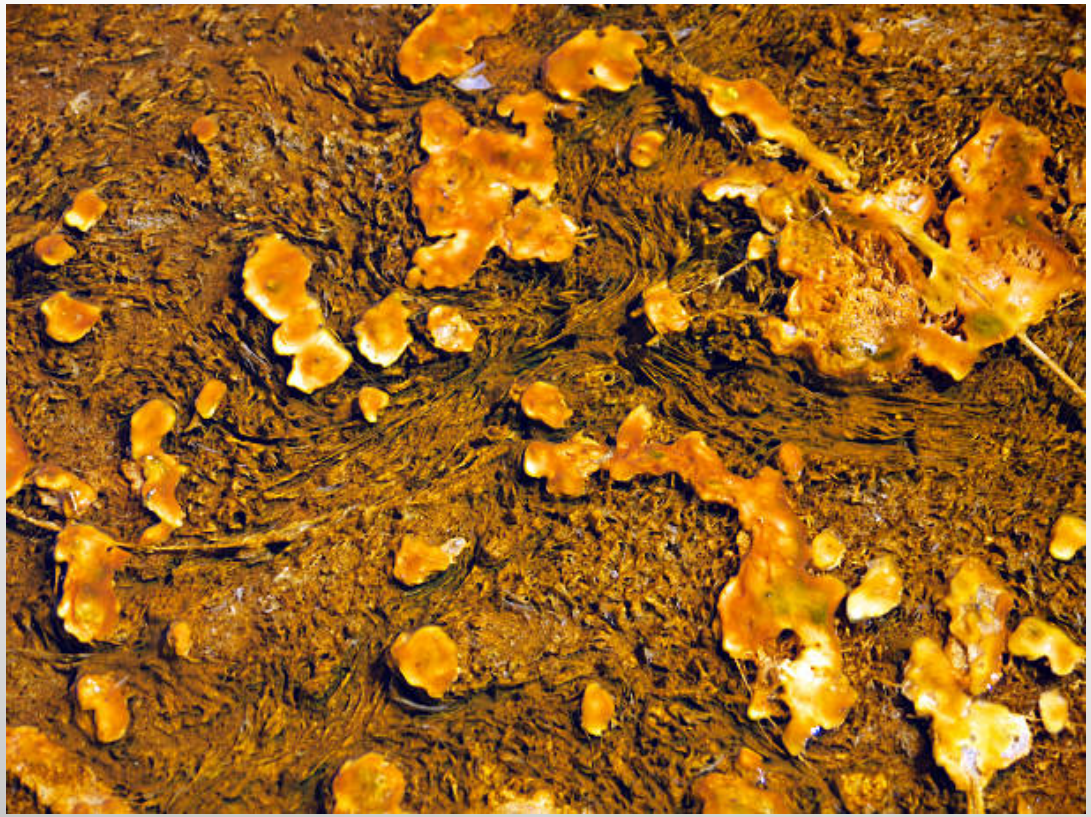


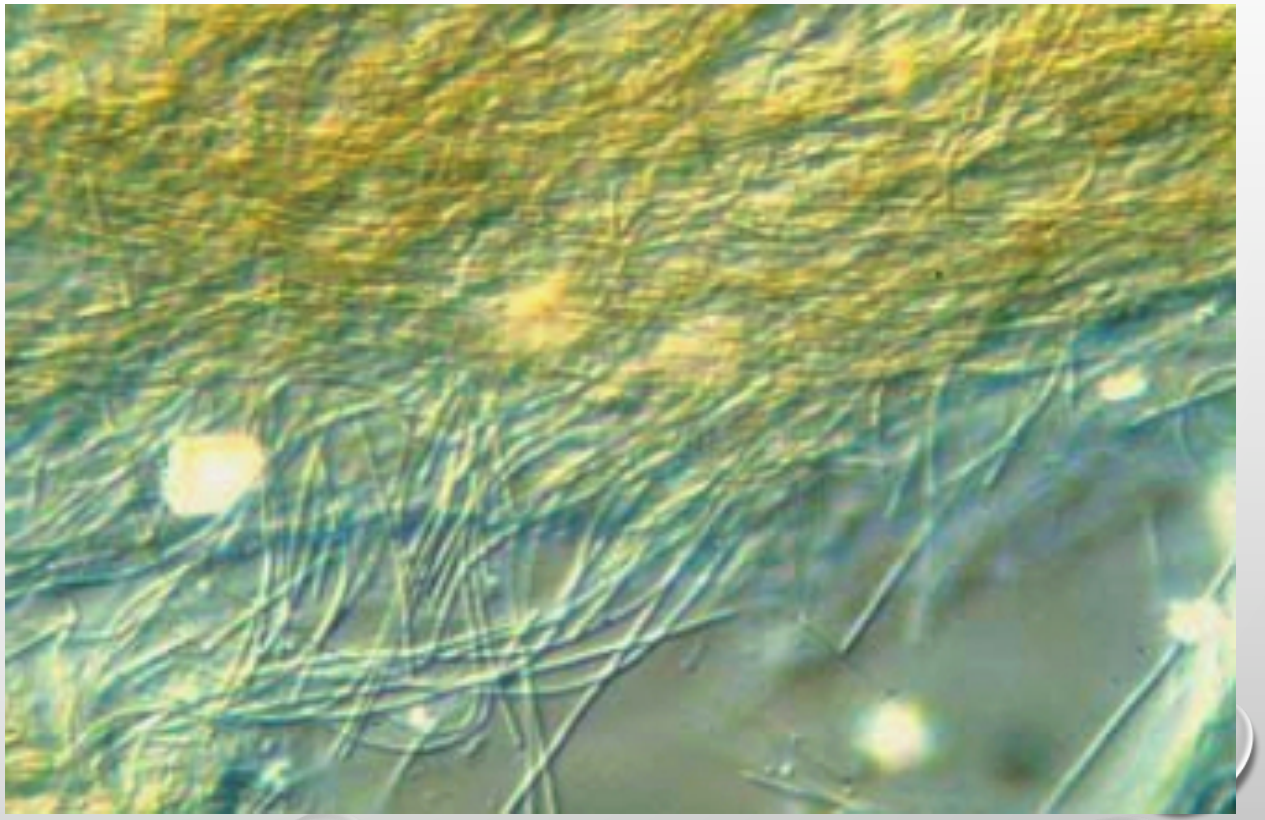
# IN HOT SPRINGS: GRAND PRISMATIC SPRING, YELLOWSTONE

# IN HOT SPRINGS: GRAND PRISMATIC SPRING, YELLOWSTONE

- LARGEST HOT SPRING IN THE US (110 METERS IN DIAMETER, 50 METERS DEEP), AND THIRD LARGEST IN THE WORLD
- THE SPRING DISCHARGES AN ESTIMATED 2,100 LITERS (560 US GALLONS) OF 70 °C (160 °F) WATER PER MINUTE
- THE DEEP BLUE COLOR OF THE WATER IN THE CENTER RESULTS FROM THE INTRINSIC BLUE COLOR OF WATER
- THE VIVID COLORS IN THE SPRING ARE THE RESULT OF **MICROBIAL MATS** AROUND THE EDGES OF THE MINERAL-RICH WATER. THE MATS PRODUCE COLORS RANGING FROM GREEN TO RED, DEPENDING ON THE RATIO OF MICROBIAL POPULATIONS

# A CLOSE-UP OF MICROBIAL MATS

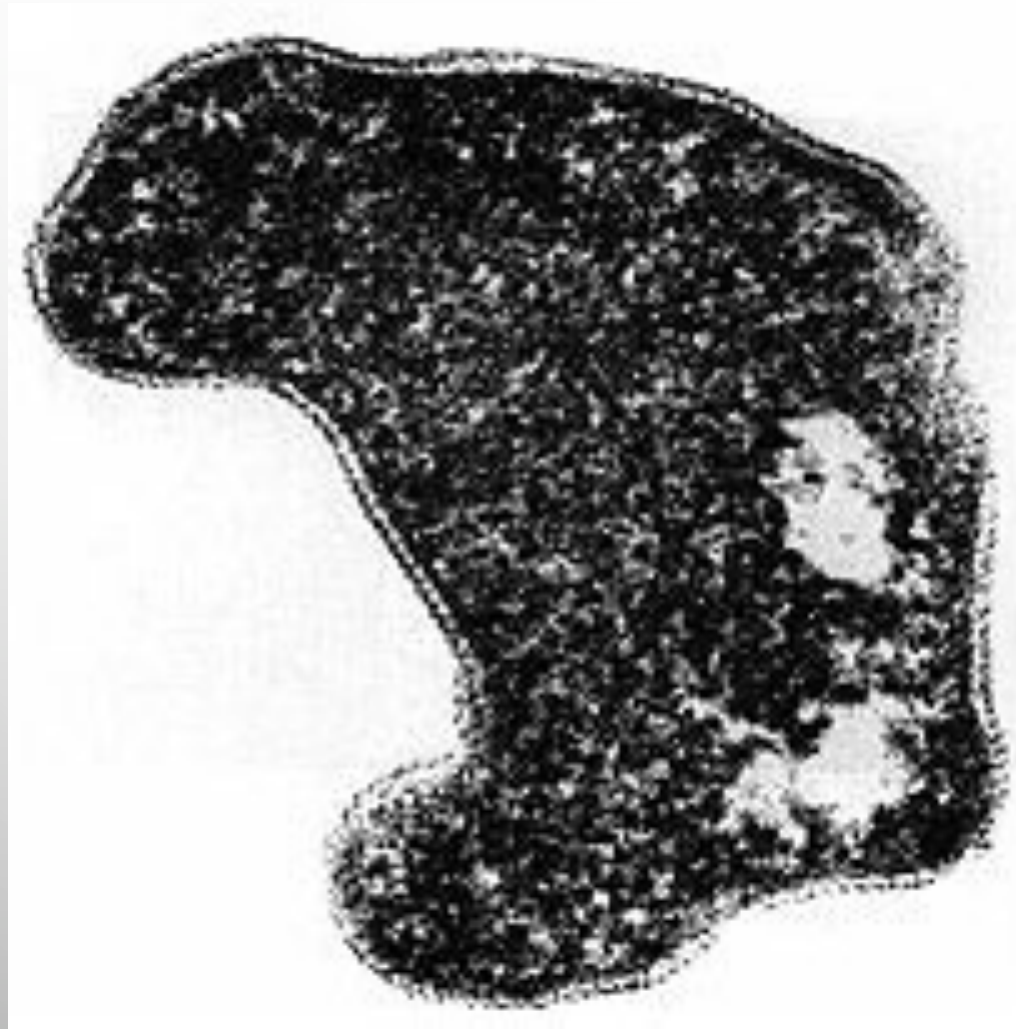


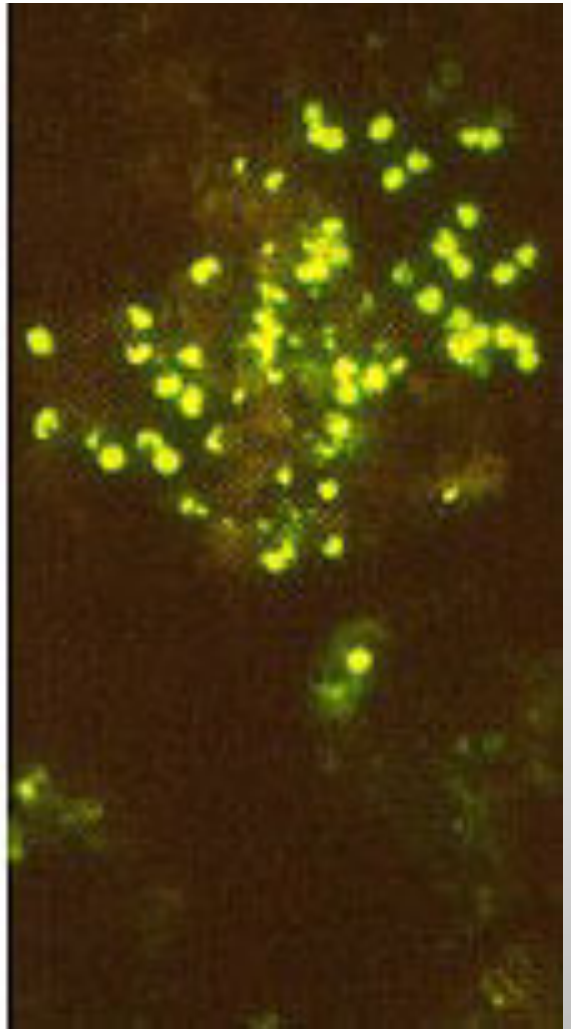


# IN BOILING MUD POTS (YELLOWSTONE)

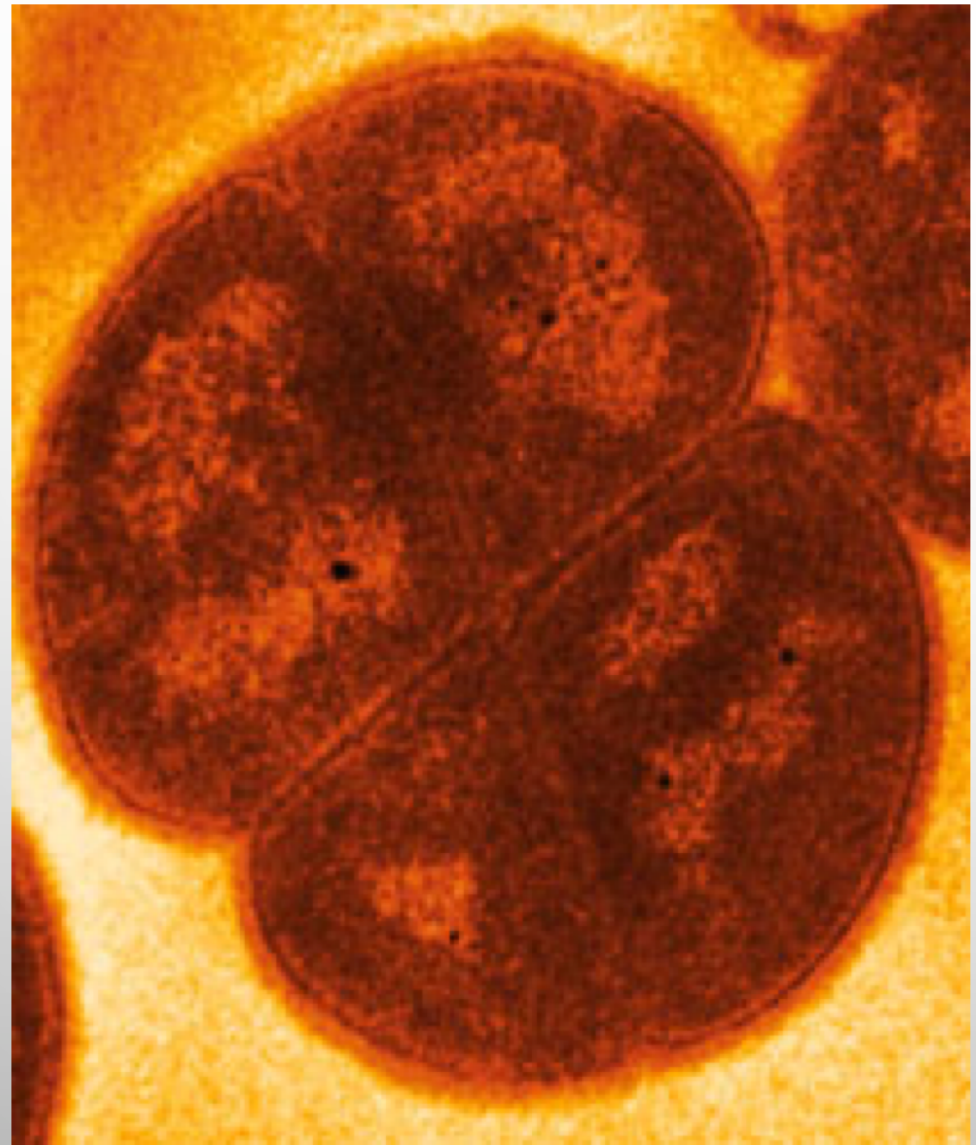
- ACIDIC HOT SPRING WITH LIMITED WATER
- IT IS THE COMBINED ACTION OF ACID AND MICROORGANISMS THAT DECOMPOSE SURROUNDING ROCK, TURNING IT INTO CLAY AND MUD.

# BOILING MUD POTS INHABITANTS





# AFTER HEAVY RADIATION EXPOSURE



*Deinococcus radiodurans*

Ubiquitous
In soils
In meat that had been sterilized using gamma radiation
Even inside nuclear reactors

# IN ANTARCTICA – LAKE VIDA

# LAKE VIDA

- THE PERMANENT SURFACE ICE ON THE LAKE IS THE THICKEST NON-GLACIAL ICE ON EARTH, REACHING A DEPTH OF AT LEAST 21 METRES
- SEVEN TIMES AS SALINE AS SEAWATER
- THE HIGH SALINITY ALLOWS THE BRINE TO REMAIN LIQUID AT AN AVERAGE YEARLY WATER TEMPERATURE OF −13 °C
- THE ICE CAP HAS SEALED THE SALINE BRINE FROM EXTERNAL AIR AND WATER FOR THOUSANDS OF YEARS

# LAKE VIDA

- IN DECEMBER 2002 A RESEARCH TEAM, LED BY UNIVERSITY OF ILLINOIS AT CHICAGO'S PETER DORAN, DISCOVERED 2,800-YEAR-OLD MICROBES PRESERVED IN ICE LAYER CORE SAMPLES DRILLED IN 1996. THE MICROBES REANIMATED UPON THAWING, GREW AND REPRODUCED

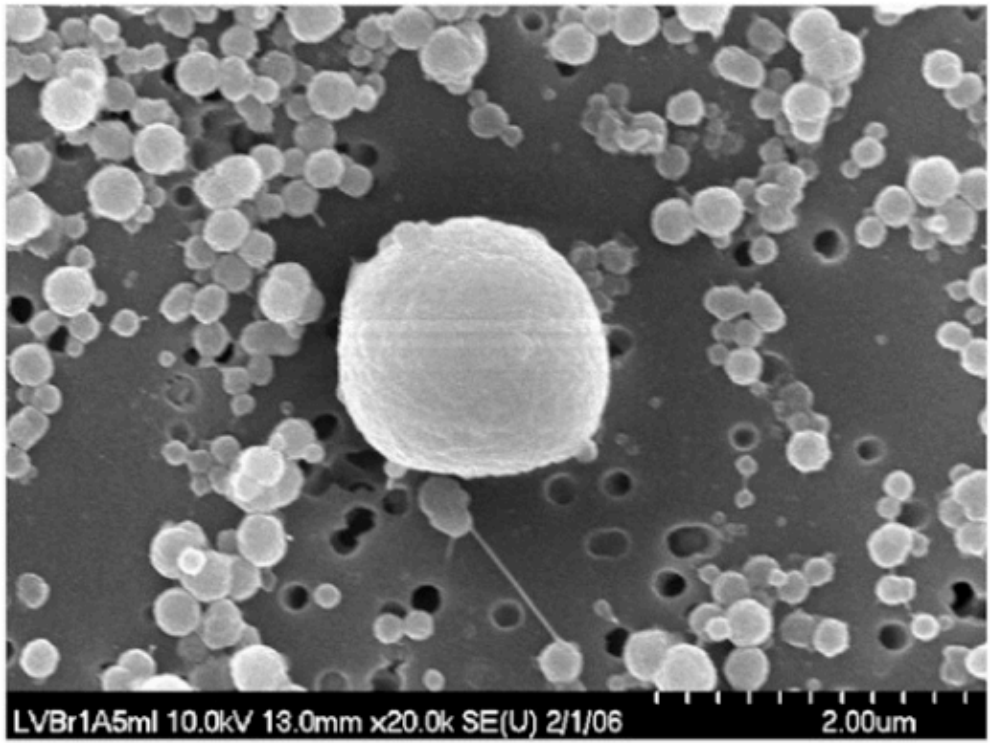
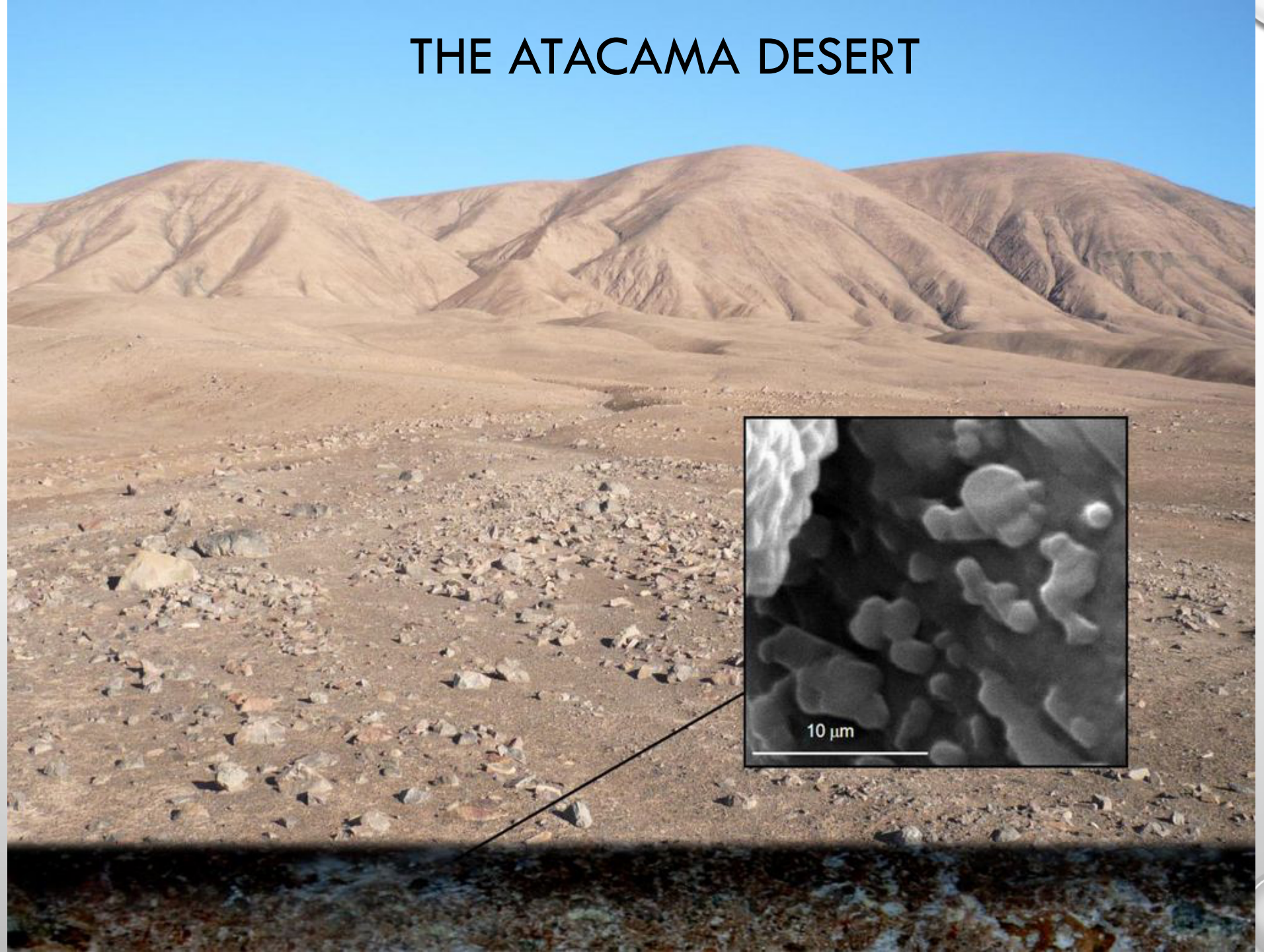
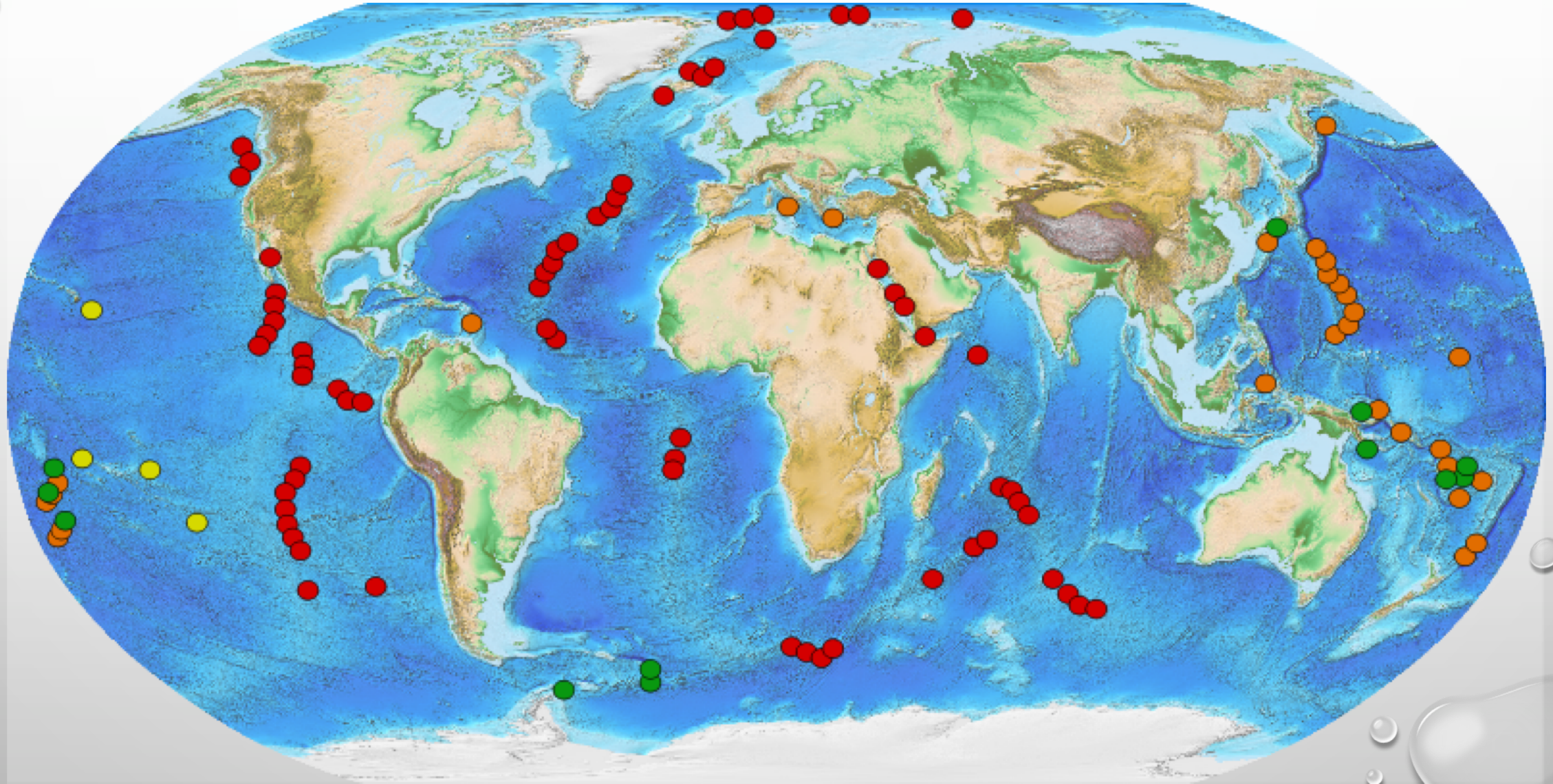



**Fig. 1.** Lake Vida brine micrograph. Scanning electron micrograph with ~1.0-mm diameter cell, and small particles (~0.2 μm in diameter). Note that the pore size of the 25-mm diameter membrane is 0.2 μm; and that 5 mL of brine was filtered onto the membrane.

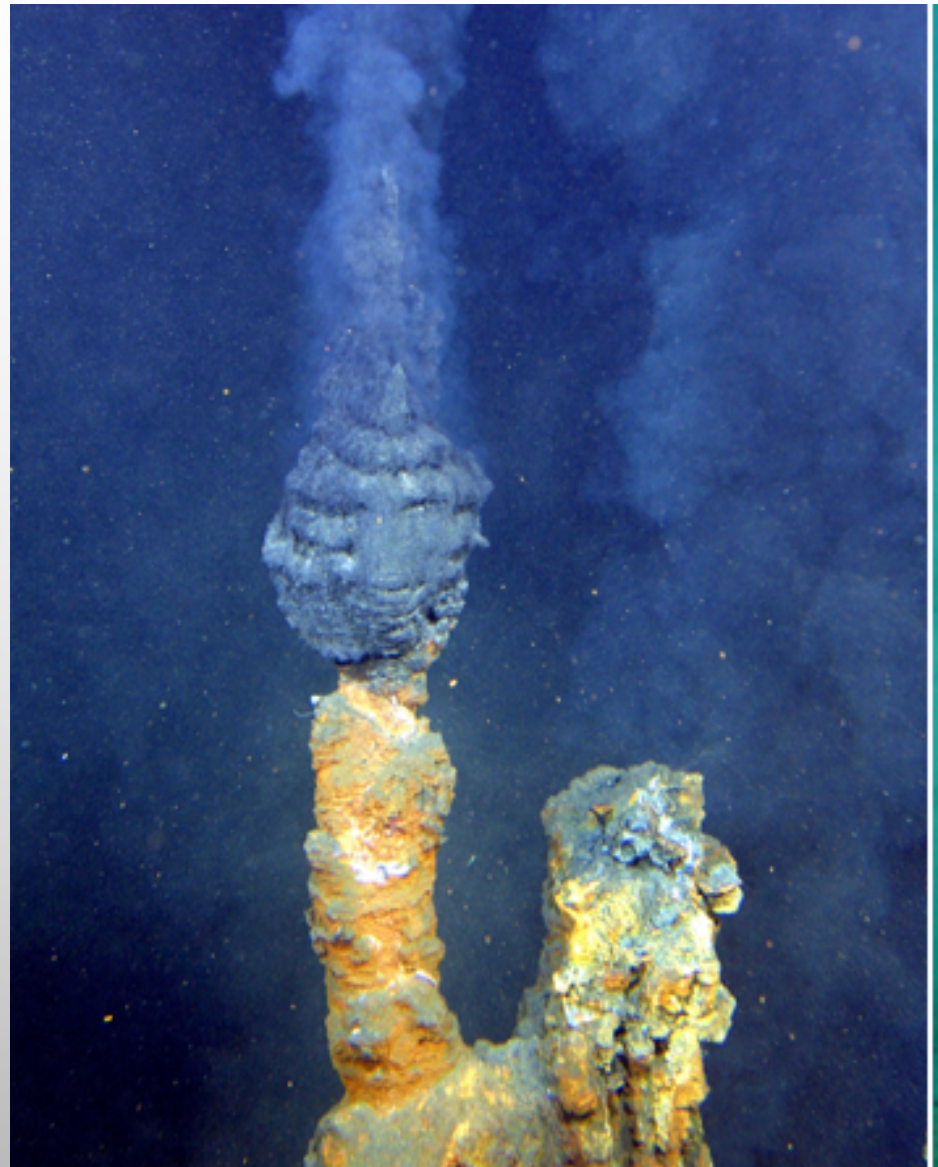
# THE ATACAMA DESERT

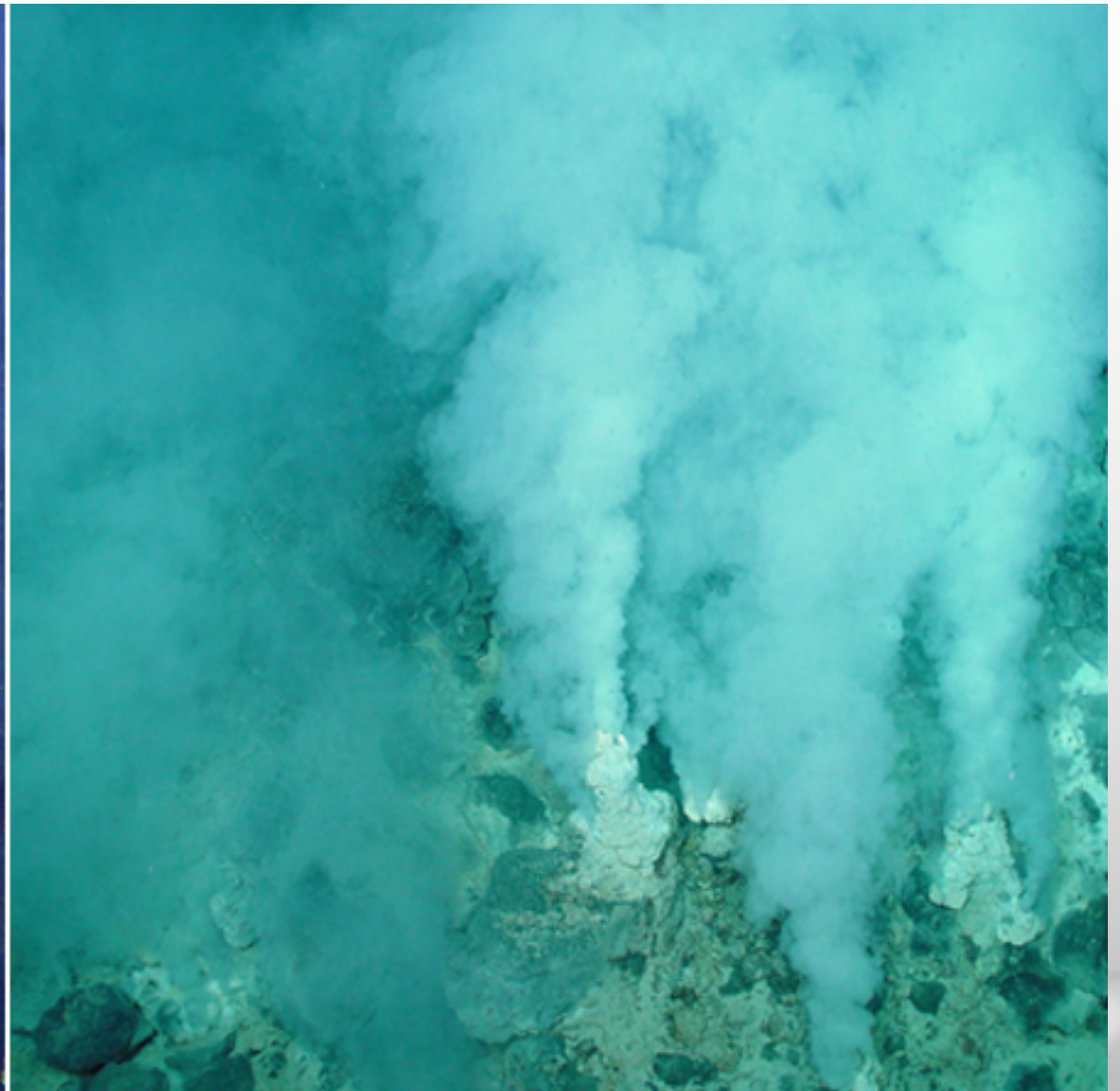


# IN DEEP-SEA HYDROTHERMAL VENTS



# HYDROTHERMAL VENTS (BLACK AND WHITE SMOKERS)





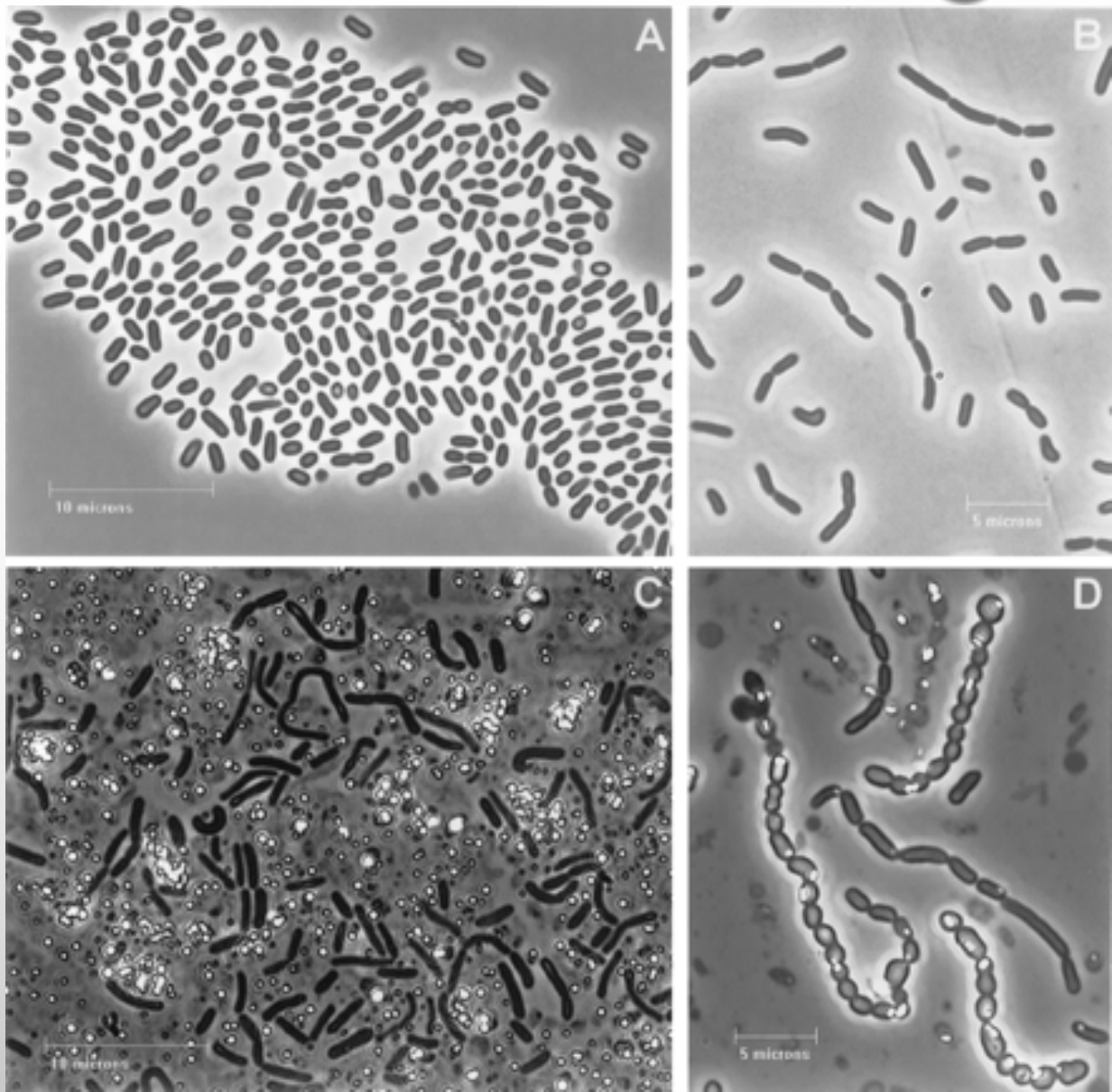
# THE RICH ECOSYSTEMS AROUND HYDROTHERMAL VENTS

# THE RICH ECOSYSTEMS AROUND HYDROTHERMAL VENTS

# WHAT DO THEY EAT????

- COMPARED TO THE SURROUNDING SEA FLOOR, HYDROTHERMAL VENT ZONES HAVE A DENSITY OF ORGANISMS 10,000 TO 100,000 TIMES GREATER
- BUT,
- NO SUNLIGHT → NO ALGAE TO SUPPLY FOOD
- MARINE SNOW: NUTRIENTS FALLING FROM DEAD MARINE LIFE, ETC., RAINING DOWN → VERY SPARSE
- PRIMARY PRODUCERS (THOSE AT THE BASE OF THE FOOD CHAIN) ARE MICROBES → USING ENERGY STORED IN CHEMICALS (MOSTLY METHANE AND SULFUR COMPOUNDS) TO PRODUCE ORGANIC MATERIAL

# HYDROTHERMAL VENT PRIMARY PRODUCERS



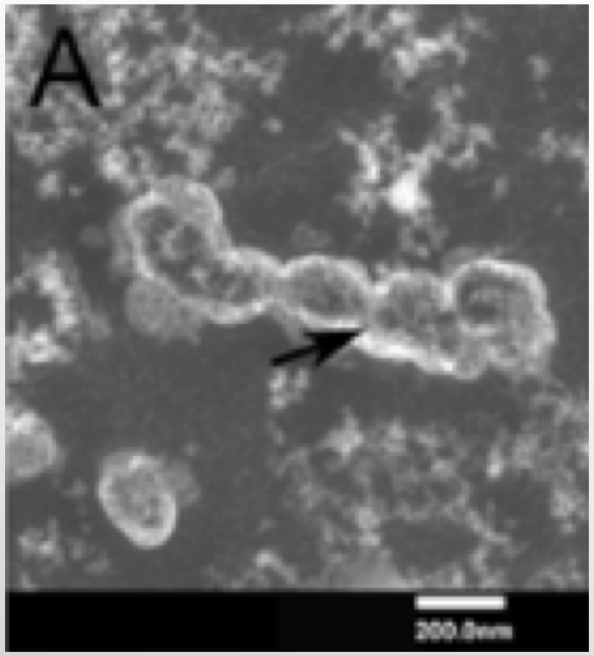
# DALLOL GEOTHERMAL AREA, ETHIOPIA'S DANAKIL DEPRESSION

# THE DANAKIL DEPRESSION

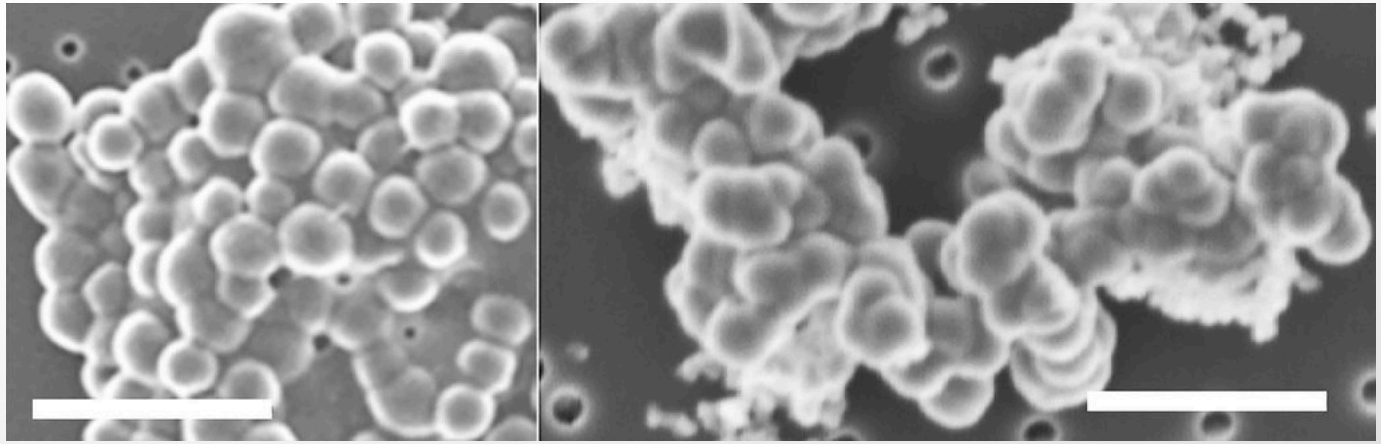
- IT LIES AT THE CONVERGENCE OF THREE TECTONIC PLATES THAT ARE SLOWLY SEPARATING. AS THE EARTH PULLS APART AND THINS OVER MILLENNIA, THE LAND SINKS ABOUT 100 METERS BELOW SEA LEVEL (ONE OF THE WORLD'S LOWEST PLACES)
- AVERAGE DAILY TEMPERATURES OF 34.4 DEGREES CELSIUS (93.9 DEGREES FAHRENHEIT)
- ONLY ABOUT 100 MILLIMETERS OF RAIN EACH YEAR
- HOT SPRINGS TEMPERATURES RANGING BETWEEN 90 AND 109 °C
- HIGHLY ACIDIC (PH ~ 0)
- HIGH SALINITY
- HIGH CONCENTRATION OF IRON AND COPPER
- HIGH CONCENTRATION OF HEAVY METALS

# THE DANAKIL DEPRESSION: DOES ANYBODY LIVE THERE?

- ULTRA-SMALL MICROORGANISMS EMBEDDED WITHIN THE PRECIPITATED MINERAL STRUCTURES




- BUT ALSO IMPOSTORS



real cells

biomorphs

# THEN, MORE SURPRISES…

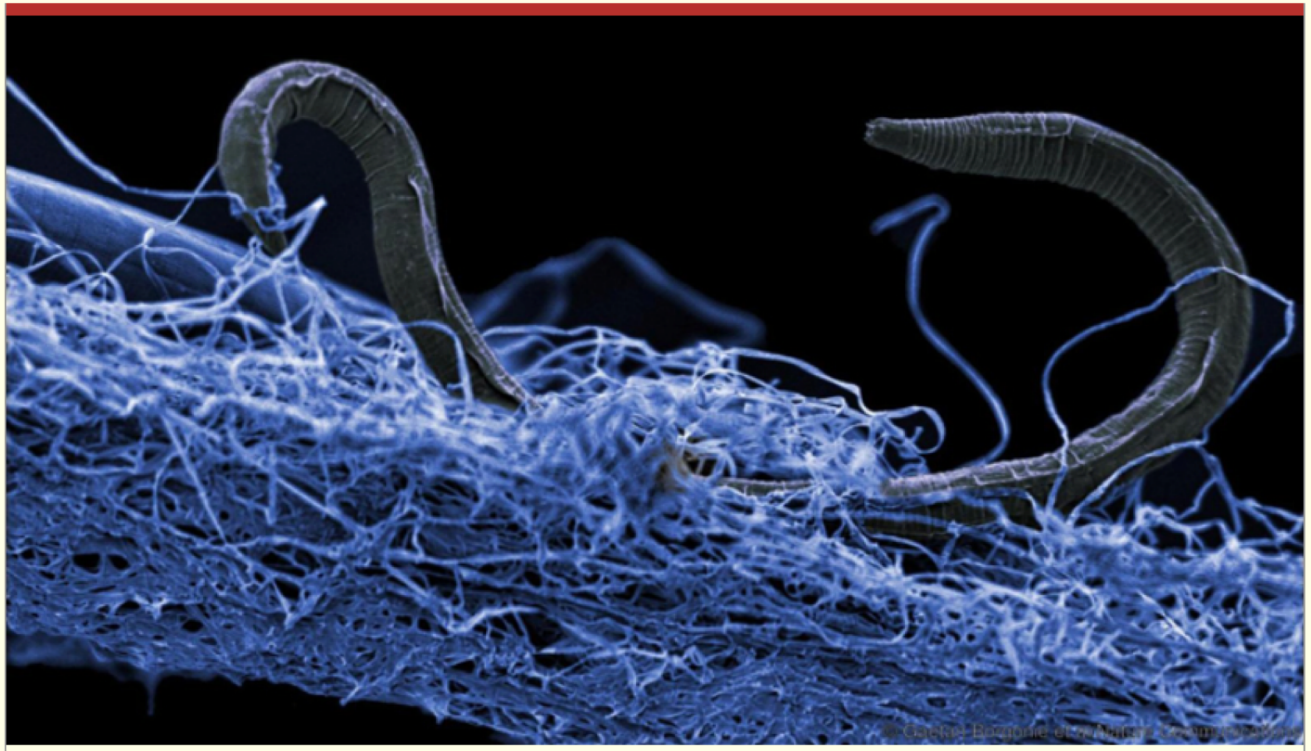
# About the Deep Carbon Observatory

**The Deep Carbon Observatory (DCO) is a global community of more than 1000 scientists on a ten-year quest to understand the quantities, movements, forms, and origins of carbon in Earth.**

# DEEP CARBON SCIENCE EXPLORES THE QUANTITIES, MOVEMENTS, FORMS, AND ORIGINS OF CARBON IN EARTH

- CARBON PLAYS A FUNDAMENTAL ROLE ON EARTH. IT FORMS THE CHEMICAL BACKBONE FOR ALL ESSENTIAL ORGANIC MOLECULES PRODUCED BY LIVING ORGANISMS. CARBON-BASED FUELS SUPPLY MOST OF SOCIETY'S ENERGY. ATMOSPHERIC CARBON DIOXIDE AFFECTS EARTH'S CLIMATE. YET DESPITE ITS IMPORTANCE, REMARKABLY LITTLE IS KNOWN ABOUT THE PHYSICAL, CHEMICAL, AND BIOLOGICAL BEHAVIOR OF CARBON IN THE VAST MAJORITY OF EARTH'S INTERIOR
- **HOW MUCH CARBON DOES EARTH CONTAIN, AND WHERE IS IT?**
- **WHAT IS THE NATURE OF THE DEEP CARBON CYCLE?**
- **WHAT FORMS OF CARBON EXIST WITHIN EARTH?**
- **WHAT CAN DEEP CARBON TELL US ABOUT THE ORIGINS OF CARBON, PREBIOTIC SYSTEMS, AND LIFE ITSELF?**

# Census Of Deep Life

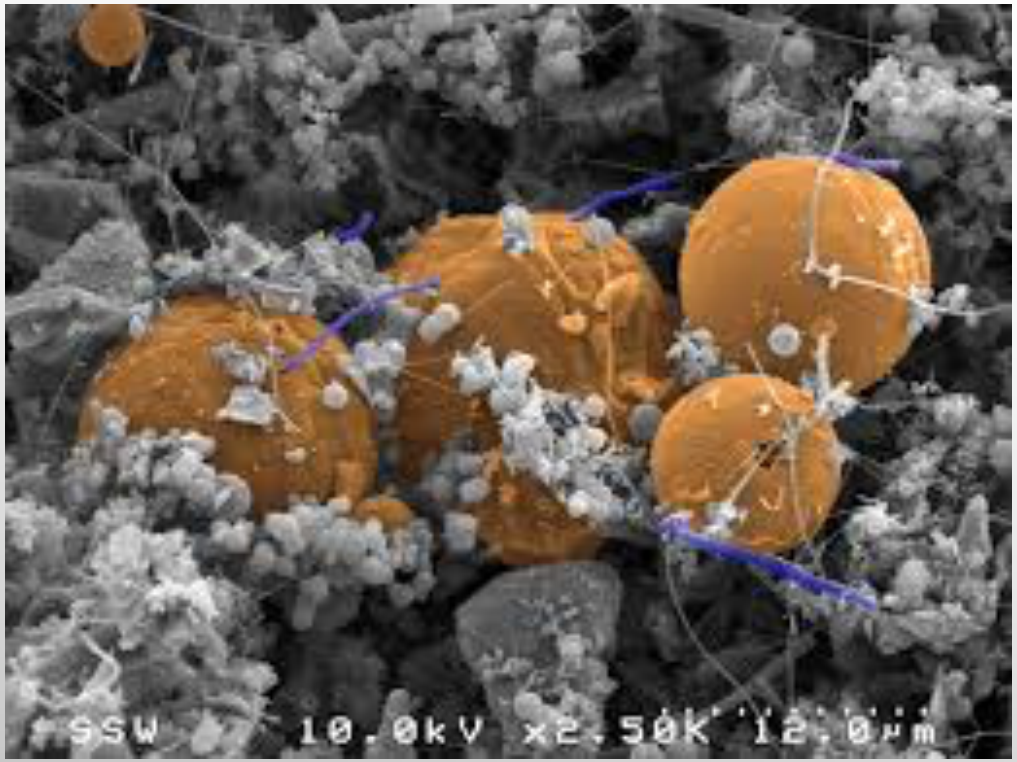


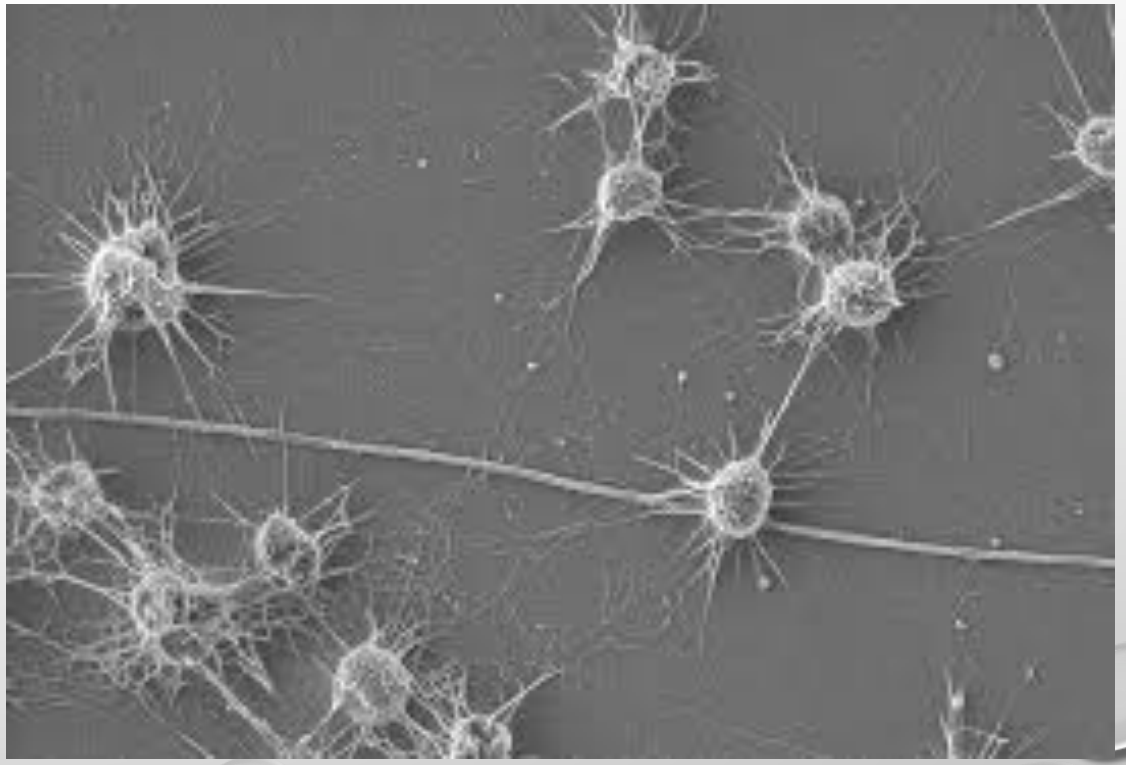
## Life In Deep Earth Totals 15 To 23 Billion Tonnes Of Carbon—Hundreds Of Times More Than Humans

Barely living "zombie" bacteria and other forms of life constitute an immense amount of carbon deep within Earth's subsurface—245 to 385 times greater than the carbon mass of all humans on the surface, according to scientists nearing the end of a 10-year international collaboration to reveal Earth's innermost secrets.

# AND SOME MUGSHOTS

## KOPANANG GOLD MINE, SOUTH AFRICA, DEPTH 1.4KM

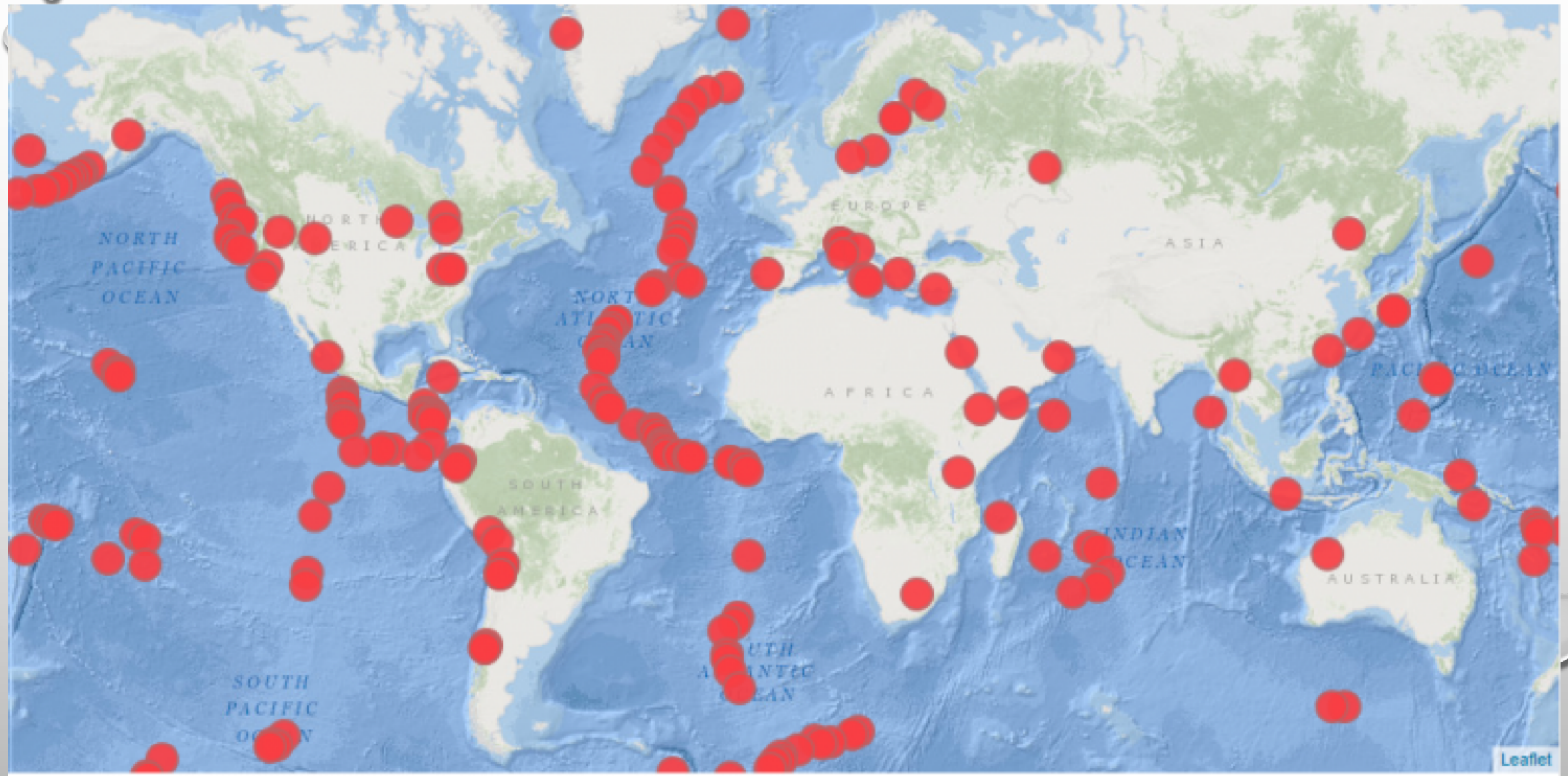


# MICROBIAL LIFE IN DEEP EARTH, OR ***MICROBIAL DARK MATTER***

- DEEP BIOSPHERE — 2 TO 2.3 BILLION CUBIC KM (ALMOST TWICE THE VOLUME OF ALL OCEANS)
- ~70% OF EARTH'S MICROBES LIVE UNDERGROUND
- 245 TO 385 TIMES GREATER THAN THE CARBON MASS OF ALL HUMANS ON THE SURFACE
- DRILLING 2.5 KILOMETERS INTO THE SEAFLOOR, AND SAMPLING MICROBES FROM CONTINENTAL MINES AND BOREHOLES MORE THAN 5 KM DEEP
- DEEP MICROBES ARE OFTEN VERY DIFFERENT FROM THEIR SURFACE COUSINS, WITH LIFE CYCLES ON NEAR-GEOLOGIC TIMESCALES, DINING IN SOME CASES ON NOTHING MORE THAN ENERGY FROM ROCKS
- THE GENETIC DIVERSITY OF LIFE BELOW THE SURFACE IS COMPARABLE TO OR EXCEEDS THAT ABOVE THE SURFACE

# DEEP CARBON OBSERVATORY SITES



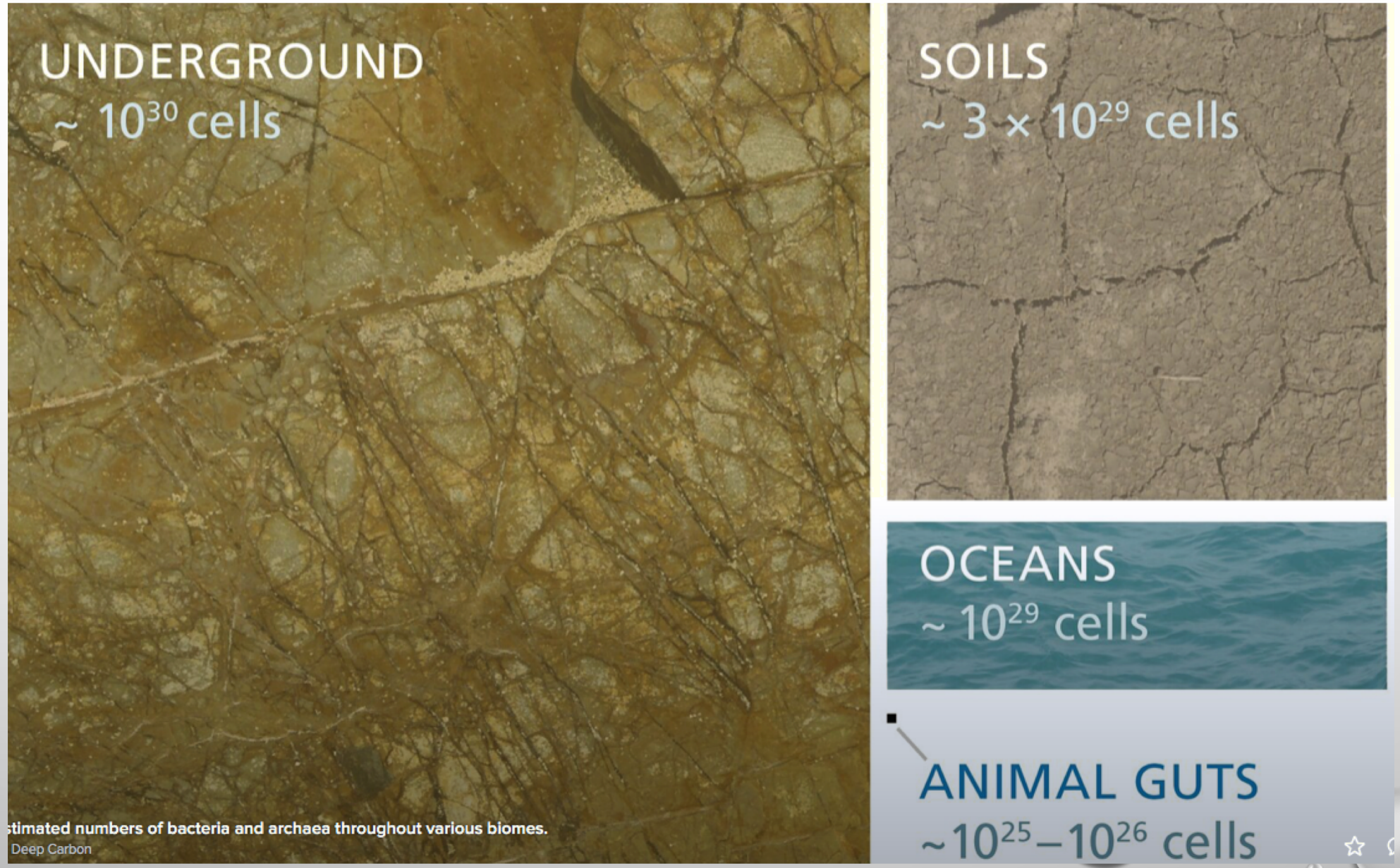
# UNANSWERED QUESTIONS

- **MOVEMENT**: HOW DOES DEEP LIFE SPREAD — LATERALLY THROUGH CRACKS IN ROCKS? UP, DOWN? HOW CAN DEEP LIFE BE SO SIMILAR IN SOUTH AFRICA AND SEATTLE, WASHINGTON? DID THEY HAVE SIMILAR ORIGINS AND WERE SEPARATED BY PLATE TECTONICS, FOR EXAMPLE? OR DO THE COMMUNITIES THEMSELVES MOVE?
- **ORIGINS**: DID LIFE START DEEP IN EARTH (EITHER WITHIN THE CRUST, NEAR HYDROTHERMAL VENTS, OR IN SUBDUCTION ZONES) THEN MIGRATE UP, TOWARD THE SUN? OR DID LIFE START IN A WARM LITTLE SURFACE POND AND MIGRATE DOWN? HOW DO SUBSURFACE MICROBIAL ZOMBIES REPRODUCE?
- **ENERGY**: IS METHANE, HYDROGEN, OR NATURAL RADIATION (FROM URANIUM AND OTHER ELEMENTS) THE MOST IMPORTANT ENERGY SOURCE FOR DEEP LIFE?
- HOW DO THE ABSENCE OF NUTRIENTS, AND EXTREME TEMPERATURES AND PRESSURE, IMPACT MICROBIAL DISTRIBUTION AND DIVERSITY IN THE SUBSURFACE?

# LET'S TALK NUMBERS: HOW MANY MICROBES ARE THERE?

- AT THE START OF THE 21ST CENTURY, ESTIMATES OF THE NUMBER OF MICROBIAL SPECIES RANGED FROM 150,000 TO A FEW MILLIONS (OF WHICH AT BEST 1,500 ARE HUMAN PATHOGENS)
- IN 2016, SCIENTISTS AT INDIANA UNIVERSITY ESTIMATED, BASED ON AVAILABLE DNA DATA, THAT THERE ARE ABOUT ONE TRILLION SPECIES OF MICROBES ON EARTH, AND 99.999 PERCENT OF THEM HAVE YET TO BE DISCOVERED
- ESTIMATED $5 \times 10^{30}$ MICROBIAL CELLS ON EARTH (FIVE MILLION TRILLION TRILLION)
- ESTIMATED CARBON: $5 \times 10^{17}$ GRAMS (HALF A TRILLION TONS)
- MICROBIAL CARBON AT LEAST EQUALS ALL CARBON IN ALL PLANTS (WHICH FAR EXCEEDS THE CARBON IN ANIMALS), MAYBE MORE THAN TOTAL PLANT AND ANIMAL CARBON COMBINED

# DISTRIBUTION OF MICROBES ON EARTH



# LIMITS OF LIFE ON EARTH

- THE ABSOLUTE LIMITS OF LIFE ON EARTH IN TERMS OF TEMPERATURE, PRESSURE, AND ENERGY AVAILABILITY HAVE YET TO BE FOUND
- MICROBIAL LIFE CAN SURVIVE UP TO 122°C, THE RECORD ACHIEVED IN A LAB CULTURE
- (BY COMPARISON, THE RECORD-HOLDING HOTTEST PLACE ON EARTH'S SURFACE, IN AN UNINHABITED IRANIAN DESERT, IS ABOUT 71°C — THE TEMPERATURE OF WELL-DONE STEAK)
- THE RECORD DEPTH AT WHICH LIFE HAS BEEN FOUND IN THE CONTINENTAL SUBSURFACE IS APPROXIMATELY 5 KM; THE RECORD IN MARINE WATERS IS 10.5 KM FROM THE OCEAN SURFACE
- (AT 4000 METERS DEPTH, FOR EXAMPLE, THE PRESSURE IS APPROXIMATELY 400 TIMES GREATER THAN AT SEA LEVEL)

# LESSONS FROM DEEP EARTH MICROBES

- BASICALLY TWO KINDS OF FEEDERS IN THE DEEP SUBSURFACE:
  - SCAVENGERS WHO SURVIVE ON LEFTOVERS OF PHOTOSYNTHESIS FROM THE SURFACE THAT HAVE BEEN BURIED FOR UP TO HUNDREDS OF MILLIONS OF YEARS
  - CHEMOLITHOAUTOTROPHS: MICROBES THAT UTILIZE CHEMICALS (**CHEMO**) FROM THE BEDROCK (**LITHO**) AS AN ENERGY SOURCE FOR MAKING THEIR OWN (**AUTO**) FOOD (**TROPH**)

- ZOMBIE MICROBES: THEY'LL REPRODUCE WHEN SOME OTHER ENERGY SOURCE COMES ALONG — AND THAT TAKES TIME, PERHAPS GEOLOGICAL TIME
- THESE DEEP-DWELLING MICROBES SEEM TO SHARE A COMMON ANCESTOR WITH SURFACE DWELLERS
- IS THIS HOW LIFE ON EARTH BEGAN???
- AND COULD THEY PROVIDE CLUES FOR LIFE IN OTHER PLANETS???

# CLUES TO LIFE ELSEWHERE IN THE UNIVERSE

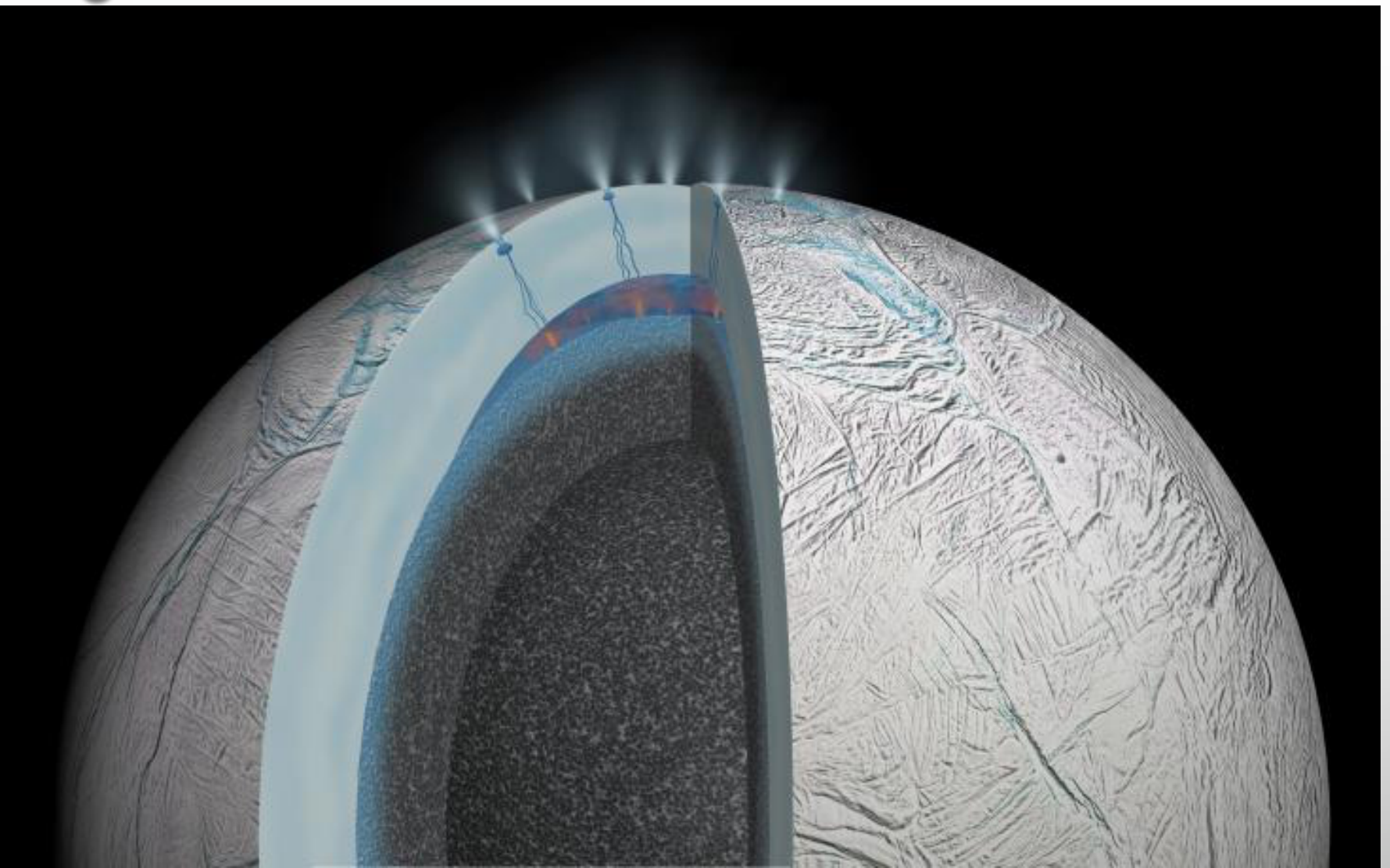
# ICE WORLDS – CLUES FROM LAKE VIDA

Natural color Enhanced color

Jupiter's Moon Europa

# LIFE ON MARS – CLUES FROM ATACAMA

# MOONS OF SATURN – CLUES FROM HYDROTHERMAL VENTS



This cutaway view of Saturn's moon Enceladus is an artist's rendering that depicts possible hydrothermal activity.
Credit: NASA/JPL-Caltech